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ASSOCIATION NOTES

SUMMER SCHOOL, 1951

We have received both considerable praise and much useful criticism from our maiden effort of organising a Summer School on "Welding Design and Engineering." The school, held at Ashorne Hill, near Leamington Spa, between 28 May and 2 June, 1951, was very well attended, and in fact there were more applicants than could possibly be accommodated. However, with some boarding out of staff and students, provision was made for a total attendance of over 200.

The School was planned to give a progressive programme from start to finish. The first few days were completely devoted to elementary or practical lectures of a general interest; the programme was then unfolded to provide for more specialised subjects and the afternoons were divided into four groups, students attending whichever group was of particular interest. In the evenings an opportunity was provided for discussions on matters of pertinent interest to the welding industry, such as testing and inspection of welded structures, and these appeared to be greatly enjoyed.

In view of the many requests for a repeat performance the Association has decided to prepare a second school to be held during the summer of 1952, and notification of entrance requirements will appear in this journal in due course.

Finally, the Association would like to take the opportunity

of using this column of *Welding Research* to thank all its many friends in the welding industry for their considerable help at the school in giving lectures, etc., and their general encouragement over the project. Also a word of thanks is due to the staff of the House at Ashorne Hill for their co-operation and helpfulness throughout the time of the school.

Summary Report on "The Behaviour and Design of Battened Structural Members"

Experiments on battened columns have been confined in the past mainly to riveted construction. The work described in this summary report was therefore undertaken with particular reference to welded joints in order to provide information on the behaviour and design of battened columns fabricated by welding.

The experimental columns consisted of two principal members with equally spaced battens; the number of battens varied from five to nine. Each of these five types of strut was tested under loads having four different values of eccentricity causing flexure about the minor axis, the loads being progressively increased to the collapse value. In addition, five struts were tested under oblique loading.

The text of the summary report deals fully with the results for one particular type of strut, but detailed experimental curves for all other tests have been omitted for reasons of space; the results from the complete series are, however, collected together to indicate diagrammatically the relationship of collapse loads with other variables. Theoretical analyses of the stresses and strains under elastic and plastic deformations were undertaken and it is concluded that the results of the elastic theory showed satisfactory agreement with the observed deflections and rotations. The collapse load calculated by an approximate plastic theory agreed well with the experimental value.

As a general conclusion to the work, attention is drawn to the preference for latticing in specifications for riveted construction; this investigation has shown, however, that with the introduction of welding there is no reason why battened construction cannot be made as rigid as latticing, and provided a satisfactory method of design can be evolved, due account of this should be taken in future specifications.

This summary was prepared for the FE.2 Committee of the British Welding Research Association on Strength and Rigidity of Welded Structural Connections, the members of the FE.2 Committee were as follows:

Professor J. F. Baker (*Chairman*)	University of Cambridge.
P. C. G. Hausser ..	R. T. James & Partners.
H. V. Hill ..	Ministry of Works (*now University of Birmingham*)
W. A. Mitchell ..	Messrs. Scott& Wilson (*now Husband & Co.*).
F. J. Samuely	

A Report on the Possibility of Developing a Weldable High Tensile Steel from 18-lb. High Frequency Melts.

This report covers the preliminary work of the FM.8 Committee of the British Welding Research Association in their effort to develop a weldable high tensile steel having a 0·2 per cent. proof stress of 30 tons per square inch. A range of steels were examined. These steels contained 0·15 per cent. carbon, 0·025 per cent. molybdenum and varying amounts of manganese, chromium and nickel.

The possibility of an 18-lb. high frequency induction furnace melt providing sufficient material for use in a modification of the "Reeve" fillet weld cracking test is discussed. With the suitability of these small experimental melts established, one steel from the proposed range of compositions was used to determine a satisfactory procedure for standardising the assessment of weldability, steel-making technique and the examination of mechanical properties.

The members of the FM.8 Committee who guided this investigation were as follows:

Dr. L. Reeve (*Chairman*)	Appleby-Frodingham Steel Co. Ltd.
Sir Donald Bailey ..	Ministry of Supply.
W. Barr ..	Colvilles Ltd.
J. Dearden ..	British Railways.
Dr. H. Harris ..	Babcock & Wilcox Ltd.
H. W. G. Hignett ..	Mond Nickel, Co. Ltd.
G. L. Hopkin ..	Ministry of Supply.
H. T. Johnson ..	Admiralty.
Dr. E. C. Rollason ..	Murex Welding Processes Ltd.
H. F. Tremlett ..	United Steel Companies Ltd.

R.70

THE BEHAVIOUR AND DESIGN OF BATTENED STRUCTURAL MEMBERS

This paper is a summary of a full report submitted by Dr. Ng and has been prepared by Jacques Heyman, M.A. A copy of the full report has been placed in the library of the British Welding Research Association, to which reference may be made for more detailed information. Although all the diagrams are not reproduced here, the figure numbers used are those of the original report. The summary was first issued to Members of the Association in July, 1950.

By WAH HING NG, M.A., Ph.D.

INTRODUCTION

A battened column is built up from principal members that carry the axial load held together at a fixed distance apart by cross-members, the battens. The present investigation is confined to columns with two principal members and equally spaced battens. The function of the battens is to transmit shear and bending moments from one main member to the other; experiments have been confined in the past mainly to work on riveted joints. It was thought that a study of welded joints would yield valuable information, and a thorough investigation of the problems was sponsored by the British Welding Research Association.

The principal theoretical work on battened columns was carried out by Engesser,[1 5 9] Krohn,[4] and Muller-Breslau.[6 8]

Engesser was concerned with concentrically loaded columns, and assumed that the two main members each carried half the load. He obtained in this way a crippling load of the Euler form, as did Muller-Breslau for eccentrically loaded struts. All this theoretical work was concerned with the elastic failure of long columns, and thus its practical application was slight. Krohn's analysis was simple to apply, but was based to a large extent on empirical formulae. However, reasonable results were obtained when he applied his theory to some experiments carried out by Emperger.[3] Apart from a few tests carried out in America,[16 19 20] the most important work was carried out by Muller-Breslau and published by Petermann[17] after his death. Petermann[18] also continued this series of experiments.

Specifications which may be considered representative of accepted American practice prohibit the use of battened columns as part of any important structure. An exception is found in the Building Code for California. The National Building Code for Canada permits the use of such columns, but the specifications seem not to be based on experiment. In Great Britain, battened columns are not permitted for girder bridges, but B.S.S. 449 (Structural Steel in Buildings) lays down specifications. These are, however, difficult to justify, and seem to favour the laced at the expense of the battened column.

In view of these prohibitions, the work described in this report was undertaken with particular reference to welded columns. Stresses and strains were investigated under elastic and plastic deformations, and it is believed that the work is the first extended investigation into this type of construction. The following were the principal factors investigated:

(1) The stability of the whole column.

(2) The strength of the batten plate as it effects the stability of the column.

(3) The spacing of the battens.

(4) The riveting or welding required to connect the battens to the main members.

(5) The influence of the rotation of the battens relative to the main members on the stability of the column.

(6) The influence of shear on the column.

EXPERIMENTAL WORK

All the strut specimens tested were nominally 6 ft. in length and were made from pressed steel channels (2½ in. by ½ in. by ⅛ in. thick) to which batten plates were welded. The number of battens varied from five to nine. Each of these five types of strut was tested under loads having four different values of eccentricity (0, ¼ in., ½ in., ¾ in.) causing flexure about the minor axis, and there were thus twenty tests in a series. Three specimens were tested under each condition to confirm values of collapse loads. In addition, five struts were tested under ½ in. oblique loading; that is, the eccentricities at the ends of the specimen were on opposite sides of the axis. Complete data of all the struts tested and of their collapse loads are given in plates 38 and 39. As each strut was fabricated it was given a serial number, to which were prefixed figures giving the eccentricity and number of battens. Thus test number 9B½E67 indicated that the strut had 9 battens and was tested under ½ in. eccentricity. This particular strut is dealt with fully in the text, as it is not possible from limitations of space to give complete sets of curves for all tests.

APPARATUS

An existing loading frame designed by Prof. J. F. Baker and Dr. J. W. Roderick[33] for their work on light alloy struts was used in the tests. This frame could exert a maximum load of 10 tons on the strut and consisted of two vertical channels (6 in. by 3 in.) which had 9/16 in. diameter holes at 2 in. pitch. This permitted struts of any length up to 10 ft. to be accommodated in the frame. To the vertical channels were attached two blocks, one termed the thrust block, and the other the plunger block. The former had a pillar resting on needle roller bearings (160 rollers, 3 mm. diameter by 15 mm. long) which permitted movement in one horizontal direction. The plunger block had a 2-in. diameter plunger which was free to move vertically and to rotate about a vertical axis. This freedom of movement was facilitated by the insertion of 624 small ($\frac{1}{8}$ in. diameter) balls between the plunger and bearing.

The load was applied by means of a lever. This had three knife edges which were in a straight line, ensuring that the lever ratio was independent of the lever itself. The exact lever ratio was found by calibration (described below). The knife edges were made of commercial alloy steel K9, having a Vickers hardness number of about 830. In the tests on light alloy struts for which the frame had been designed, the axial load was transmitted by means of 2 in. diameter hardened steel balls resting on K9 anvils. In order to obtain accurate measurements of eccentricities, those balls were replaced by knife edges. The end of the strut was held in an end fitting which consisted of a hardened plate 6 in. by $\frac{3}{4}$ in., on which a mild steel plate could slide between guides. On the mild steel plate was a Vee for holding the knife-edge. Provision was made for bolting the mild steel to the hardened plate so that the eccentricity of the knife edge with respect to the axis of the strut did not change during a test. This eccentricity could be measured accurately.

Initially one knife edge was used in each end fitting which permitted rotation about the weaker axis of the strut (YY axis in plate 1B). After the testing of the twenty-fifth strut this single knife edge was replaced by a fitting employing two knife edges. It consisted of a hardened block $4\frac{1}{2}$ in. square by $1\frac{1}{2}$ in., with two knife-edge grooves $\frac{3}{4}$ in. deep cut on each side at right angles. This system permitted free rotation about a point in the block at the intersection of the two knife edges, which were cut away at this point; in effect, therefore, a point load was applied to the specimen. In practice, all the struts failed about their weaker axis, but no bending moments were introduced about the major axis.

Another new feature was introduced at this stage. The angular position of the lever about a vertical axis affected directly the angular position of the top of the strut, and it was not possible to be certain that twisting moments were not being introduced. It was also impossible for the top of the strut to rotate freely with respect to its bottom. In order to eliminate these effects it was decided to insert a thrust bearing between the bottom of the 2 in. diameter plunger and the top end fitting. The bearing chosen was of the tapered roller type made by Timken (Code No. 78250/78551), and was specified to withstand a thrust of 10 tons, to have as small a resisting torque against torsion as possible, and to remain concentric over a small range of relative rotation. Under preliminary tests it was found impossible to rotate the bearing by hand under an axial load of only 2 tons, due to the rollers bearing hard and locking on the roller guide. This guide was ground off and a detachable collar fixed in its place; the collar was removed under a small load, and the bearing then behaved satisfactorily.

Mercer dial gauges were used to measure deflections, and were held by a frame independent of the main apparatus. Optically plane mirrors ($\frac{1}{2}$ in. diameter) in holders were used to measure rotations, connected to the centres of the batten plates by means of 4BA studding through clearance holes. (It was considered that these small holes did not materially affect the batten plate stresses.) To measure the rotation of the end battens, mirrors were attached to the end fittings. Another mirror to measure the relative twist between the plunger and the top batten plate was placed at the bottom of the plunger. All these mirrors were in a vertical plane and were read by one theodolite so placed that all the mirrors could be read by rotation about a horizontal axis. A sheet of 1/10 in. squared graph paper was used as scales in both horizontal and vertical directions. This was pinned to a drawing board, and readings obtained in this way are referred to as board readings. The size of the squares on the graph paper was measured by a standard steel scale before each test. Horizontal datum lines on a long post S placed behind the mirrors at the same distance from them on the board were

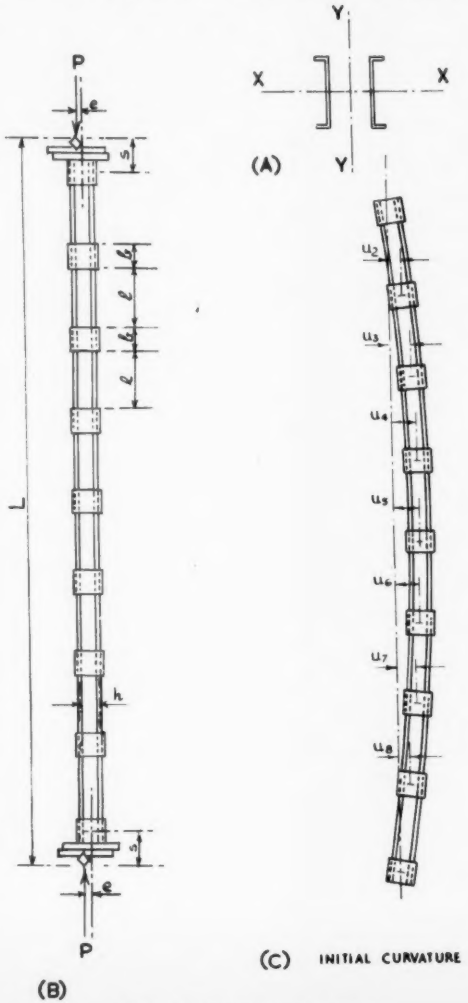


PLATE 1.—Notation used in text.

used to bring the theodolite to the same position for reading each mirror. The datum lines and the board were thus in focus together.

Mirror extensometers of 1 in. gauge length were used to measure the axial strain, and hence the axial load in individual channels between battens; these extensometers were designed by Dr. J. W. Roderick. Fixed telescopes were used to read these mirrors.

In the case of a 9 batten strut, in addition to three sets of extensometers, 10 other mirrors and 15 Mercer dial gauges were required.

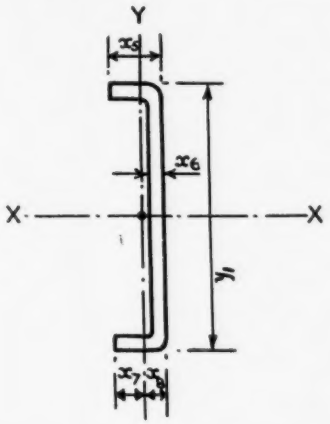
CALIBRATIONS

The following calibrations were carried out:

(*a*) *Loading Lever.*—The lever consisted of a 4 in. by 3 in. RSJ, with three knife edges in line. Direct measurement of the lever ratio was not accurate, and an indirect calibration was carried out by means of a bar of spring steel. (The method has been described by Prof. J. F. Baker and Dr. J. W. Roderick[32].) The lever ratio was found to be 24·80, and it exerted a force at the fulcrum of 0·3987 tons due to its own weight. The container for lead shot weighed 72·06 lb.

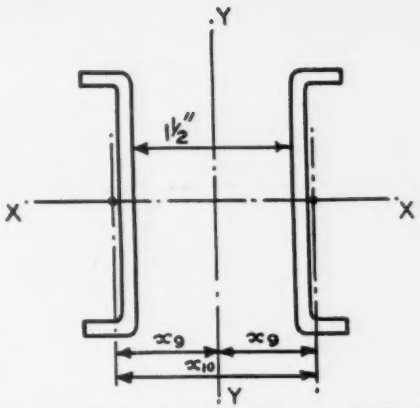
(*b*) *Mirror Extensometers.*—The distance between the blades of the knife-edges were obtained by magnifying 50 times on the Hilger optical projector.

(*c*) *Tapered Roller Thrust Bearing.*—The calibration was necessary to give some idea of the starting torque for various values of axial load, but the results were not used in any calculation as they were outside the scope of the investigation. This torque resisting relative rotation of the top and bottom of the strut was very small.



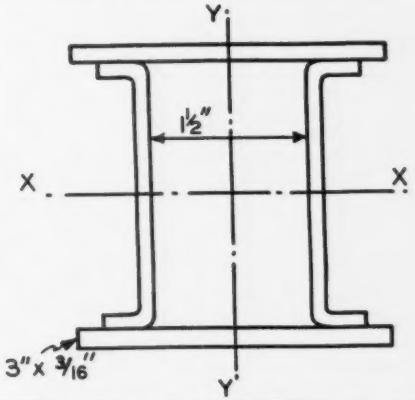
Single Channel	Nominal Section	Actual Section
y_1	2·50	2·5396
x_5	·50	·5100
x_6	·125	·1274
A_1	·4062	·4021
Ixx	·2950	·2877
I_1	·0060	·0062
Kxx	·8521	·8459
K_1	·1217	·1242
Z_7	·01580	·01615
X_7	·3798	·3839
Z_8	·04992	·04917
X_8	·1202	·1261

PLATE 18(a).—Properties of Single Channel cross-section.



Two Channels	Nominal Section	Actual Section
A_2	·8124	·8042
Ixx	·5900	·5754
I_2	·6272	·6297
Kxx	·8521	·8459
K_2	·8787	·8849
X_9	·8702	·8761
X_{10}	1·7404	1·7522

PLATE 18(b).—Properties of Two Channel cross-section.



Joint	Nominal Section	Actual Section
A_3	1·9374	1·9292
Ixx	2·4765	2·6704
I_3	1·4710	1·4734
Kxx	1·1306	1·1765
K_3	·8714	·8739

PLATE 18(c).—Properties of Joint cross-section.

FABRICATION OF SPECIMENS

The loading frame was designed for a maximum of 10 tons axial load, and this imposed a limit on the area of cross-section of the strut. It was proposed to make the strut 6 ft. in length with a slenderness ratio of about 85. Assuming that the formula given in B.S.S.449 obtained, this gave the concentric failing load as 10·86 tons per sq.in. Thus for a maximum of 10 tons, the area of cross-section was not to be greater than 0·9205 sq.in. It would have been preferable from the point of view of calculation to use rectangular main members, but in order to obtain slenderness ratios of from 50 to 120 the free length between battens would have to be small. A large number of battens would therefore have to be used, increasing the difficulties of welding and giving untypical struts. I-sections of the small size necessary for these experiments are not rolled, but the Crittal Manufacturing Company kindly consented to press some channels for the purpose of this research. The nominal section was 2½ in. by ½ in. outside dimensions and ⅛ in. thick, giving an area of 0·4062 sq.in. As these channels were pressed from flat plates, the outside corners were not sharp, and this added to the difficulties of welding. The exact form of the corners was found by magnifying representative sections in the Hilger optical projector. Using the values obtained in this manner, the total area as measured was found to be 0·4021 sq.in., the minimum I 0·0062 in⁴., and the distance to the neutral axis 0·1261 in.

The batten plates were 3 in. by 2½ in. by 3/16 in., and the length of the nominal ¼ in. fillet welds used was 2½ in. These welds were not returned at their ends, as it was considered desirable not to weld across the channels. Plates 18 and 19 show the struts used with their various properties.

The channels when received were tested for straightness; where required they were straightened manually. The struts were fabricated in the welding shop of the engineering laboratory, Cambridge University. Due to the thinness of the channel sections and to the fact that they had been cold pressed, it was feared that the heat of welding would distort the strut. These fears were justified, and in order to reduce the bowing and twisting as much as possible, constant welding conditions were adopted. R 217 classification type gauge 10 electrodes were used with a current of 115 amperes. Detailed attention was paid to the order of welding the battens, and a system was worked out which reduced the distortion to a minimum. Before the 2½ in. welds were run, all the battens were tacked to the channels. The final order of welding which gave minimum distortion is shown in Plates 21 and 22.

After the welding, the ends of the specimens were turned plane and perpendicular to the axis. The positions of the dial gauges were scribed, centre lines marked, and the clearance holes for the 4BA studs holding the mirrors were drilled at the centres of the battens.

TEST PROCEDURE

The following preliminary measurements were made:

(1) Overall length between the milled ends.

(2) Initial curvatures of the two channels (east and west faces). Dial gauges were set over the scribed points and a straight line datum obtained by means of a straight edge. The curvature of the north and south faces was also recorded for record purposes.

(3) Relative twist of the ends of the specimen. Originally the measurements were gauged by eye, but finally a theodolite was used to obtain more accurate observations.

Before setting up the specimen in the testing frame, the latter was carefully prepared. The intersection of the double knife edge at the bottom was placed directly beneath the centre line of the 2 in. diameter plunger with the aid of a plumb line. The mild steel plate was bolted to the hardened plate in the end fitting to ensure the correct eccentricity for any test, and the ends of the strut were bolted centrally in the end fittings. After the strut had been fitted with its mirrors and extensometers, the whole was placed in the

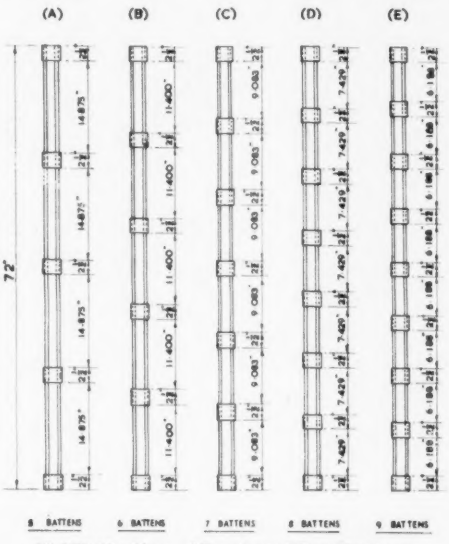
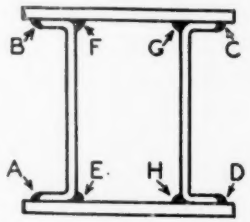


PLATE 19.—Types of Experimental Strut Specimens.

(A)

CROSS SECTION OF STRUT AT JOINT



(B)

9 Batten Strut	Outside Welds					Inside Welds				
	Joint No.	A	B	C	D	Joint No.	E	F	G	H
	1	30	36	33	31	1	31	33	35	29
	2	27	21	24	26	2	23	32	30	21
	3	14	20	17	15	3	15	24	22	13
	4	11	5	8	10	4	7	16	14	5
	5	1	4	3	2	5	3	2	1	4
	6	6	12	9	7	6	9	8	6	11
	7	19	13	16	18	7	17	10	12	19
	8	22	28	25	23	8	25	18	20	27
	9	35	29	32	34	9	36	26	28	34

(C)

8 Batten Strut	Outside Welds					Inside Welds				
	Joint No.	A	B	C	D	Joint No.	E	F	G	H
	1	32	25	28	30	1	22	29	31	24
	2	18	24	21	19	2	14	21	23	16
	3	15	10	11	14	3	6	13	15	8
	4	1	7	6	4	4	4	5	7	2
	5	8	2	3	5	5	12	3	1	10
	6	9	16	13	12	6	20	11	9	18
	7	23	17	20	22	7	28	19	17	26
	8	26	31	29	27	8	32	27	25	30

PLATE 21.—Welding Procecure.

(A)	Outside Welds					Inside Welds				
7 Batten Strut	Joint No.	A	B	C	D	Joint No.	E	F	G	H
	1	28	21	26	23	1	28	21	23	25
	2	13	18	15	20	2	22	13	15	24
	3	10	7	12	5	3	14	5	7	16
	4	3	4	1	2	4	1	4	3	2
	5	11	6	9	8	5	6	11	9	8
	6	16	19	14	17	6	12	19	17	10
	7	25	24	27	22	7	20	27	26	18
(B)	Outside Welds					Inside Welds				
6 Batten Strut	Joint No.	A	B	C	D	Joint No.	E	F	G	H
	1	18	24	21	19	1	14	21	23	16
	2	15	10	11	14	2	6	13	15	8
	3	1	7	6	4	3	4	5	7	2
	4	8	2	3	5	4	12	3	1	10
	5	9	16	13	12	5	20	11	9	18
	6	23	17	20	22	6	24	19	17	22
(C)	Outside Welds					Inside Welds				
5 Batten	Joint No.	A	B	C	D	Joint No.	E	F	G	H
	1	15	20	13	18	1	18	13	15	20
	2	12	5	10	7	2	14	5	7	16
	3	2	3	1	4	3	1	4	3	2
	4	9	8	11	6	4	6	11	9	8
	5	14	17	16	19	5	12	19	17	10

PLATE 22.—Welding Procedure

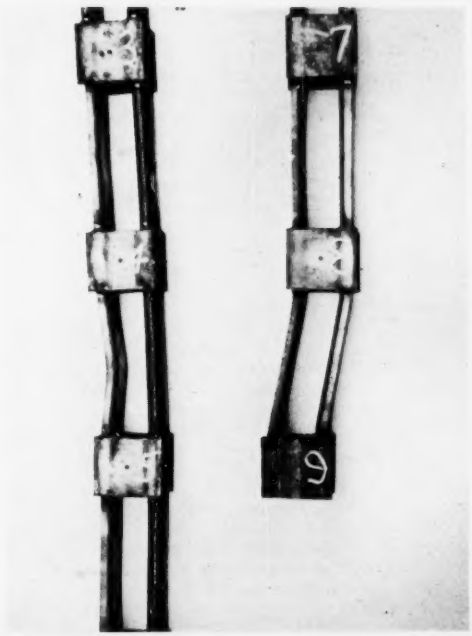


PLATE 26B.—Illustration showing two modes of failure. One channel bent in single curvature, on the left, and on the right two channels bent in double curvature.

loading frame between the double knife edges, the weight of the roller bearing at the top being sufficient to keep the strut in place. Dial gauges were placed in the dial gauge frame in the correct positions. In addition to these, two dial gauges were placed, one at the top and the other at the bottom, to measure the contraction of the strut under load. Three dial gauges were also placed on the north face to measure deflections about the major axis. (These latter gauges gave consistently small readings, showing that the strut had been set up accurately and that it was straight.) Before starting the test, the scale distances between the mirrors and the board and the height of the mirrors above the ground were measured; the correction on the graph paper on the boards due to its expansion or contraction was also taken.

Readings were first taken at no load. (For a 9 batten specimen 30 readings were required for each increment of load.) The lever was then placed in position and the detachable collar on the roller bearing was removed. The axial load was now 0·3937 tons and a small container with lead shot (weight 9 lb. 2½ oz.) was added to bring the increment up to 0·5 tons. A set of readings was taken, and the load on the specimen increased to 1 ton. After another set of readings, the small container was gently removed and replaced by the large container used throughout the remainder of the test. The addition of a small amount of lead shot brought the total up to 1·5 tons. For test 9B½E67, further increments of 0·5 tons were added until a total of 5·0 tons was reached, after which four increments of 0·2 tons made the total load 5·8 tons. The increment was then reduced to 0·1 tons, the strut failing at 6·1 tons.

At a load of 2 tons, a Mercer dial gauge was attached to the container to give sink readings. Although this gave no reliable information as to the deformation of the strut, an indication of the onset of creep could be observed (at 3·0 tons for test 9B½E67). Readings of this gauge were taken at intervals of a minute at loads of 5·2 tons and above. At the end of the test, a photograph was taken for record purposes and to show the mode of failure. For each mirror, the average between the maximum and minimum readings was calculated, and the height of the board reading corresponding to this measured. This was necessary to reduce the rotations of the battens to radian measure.

For test 9B½E67 four preliminary runs were undertaken up to an axial load of 2·5 tons. The dial gauges and mirrors returned to their zeros on removal of this load, and the deflection and rotation curves were substantially similar, showing that no part of the strut had been stressed beyond the yield point. The fifth run was the one described above when the test was continued until failure occurred. At a load of 6 tons the central deflection of the strut was over ½ in., and the rate of the sink of the container also showed that collapse was imminent. It was of interest to find the deformations of the strut just before collapse, and to do this the container was allowed to descend only a little at a time, Meanwhile readings of deflection and rotation were taken, and it was easy to observe when batten No. 9 reversed its direction of rotation. The strut failed between panels points 7 and 8, and the channels were bent in double curvature.

Generally, most struts failed either in one or other of the end panels or in the panel next to these; failure was by double curvature bending. In some cases, however, if the container was not allowed to descend freely, the centre panel failed in single curvature (plate 26B). The failing load for similar struts collapsing in different modes was nevertheless the same. The two channels in the end panel at a condition just before collapse are bent in double curvature, while the centre channels were bent in single curvature. The relative deflection of the ends of the end panel was very much greater than that of the centre, and the axial load in the end channel was slightly smaller than that of the centre. When the

container was allowed to descend without restraint, the channels in the end panel were deformed at a faster rate than those at the centre; with the rate of descent controlled, however, there was more chance of larger control deflections occurring, leading to a larger load in the channel at the centre.

In none of the specimens tested was there any failure in the joints. The welds were examined carefully and there were no cracks.

The roller bearing behaved satisfactorily. The horizontal readings showed that rotation occurred between the plunger and the top of the strut, so that the strut was not twisted as the lever descended. There was no torsional failure in any specimen.

EXPERIMENTAL RESULTS

A complete set of curves for test 9B½E67 is given in plates 54, 55 and 56.

Plate 54 shows the deflections, which, as expected, do not increase linearly with load. It is difficult to tell from these curves when yield was reached, as the slopes are smooth.

Plate 55 shows the rotations of the panel points, and plate 33A the contraction of the strut. The dotted line is a calculated curve neglecting shortening due to bending; it will be seen that the experimental curve departs from the straight line at about 3 tons.

The force in the member AC is plotted in plate 56, and it will be seen that it is nearly linear and only a little less than the total load on the strut.

A mechanical analysis of the fibre stresses was undertaken which made use of the experimental deflections and rotations. In the first instance the assumptions were made that the difference of rotations between the edges of the battens at the two ends of the panel considered was dependent only on the difference in contraction of the channels (these contractions being due to the axial forces only), and that the bending moment at the end A of channel AC was equal to that at the end B of BD (*see* Plate 35c). The fibre stresses at points 5 and 8 were calculated according to these assumptions and gave curves (*a*) in plates 35a and 35b. These are extremely irregular, and similar curves plotted from smoothed readings of deflection and rotation give little better results. The analysis requires small differences of large quantities, and any small error in the observations completely upset the calculations.

Another analysis was undertaken on the assumption that the four end moments of the channels in the end panel were equal. This curve ((*c*) in Plate 35) was very smooth, and agreed well with the theoretical (*d*). It will be seen that compressive yield at 18 tons per sq.in. was reached at P = 4·70 tons. In the theoretical elastic analysis, $M_{CA} > M_{AC}$, and therefore there is reason to believe that the point 5 reached yield with P much less than 4·70 tons. This would confirm the experimental results where creep was first noticed at P = 3·0 tons.

After the beginning of compressive yield, no useful purpose would be gained by calculating fibre stresses, but the analysis was continued in order to find R_{AC} (the force in channel AC), and the end moments in the channels. Plate 36a shows three curves of R_{AC}: (*a*) was derived from the mirror extensometer readings; (*c*) from the assumption that the four end moments were equal; and (*d*) was the theoretical curve from the elastic analysis.

The derivation of the full plastic moment (*mf*) is described below. Plate 36b shows *mf* corresponding to the observed value of R_{AC} plotted against the axial load P. The observed value of M_{CA} is also plotted, and the point of intersection of the two curves gives the collapse load. (5·71 tons, 7 per cent. less than the experimental value of 6·10 tons.) For comparison, theoretical curves are plotted on the same graph.

The maximum initial curvature was added to the initial eccentricity to give the resultant eccentricity. The results are shown reduced and cross-plotted in plates 43, 44 and 45.

Both the number of battens and the eccentricity have important effects on the collapse loads. As would be expected, increasing the number of battens increases the collapse load, but from Plate 45 it will be seen that the maximum collapse load was nearly reached with 9 battens.

Plate 46 gives the results plotted in a different manner, the collapse load being plotted against end bending moment.

MISCELLANEOUS TESTS

Two tests (S9B½E69, S9B½E70) were undertaken on struts with ¼ in. tack welds instead of the normal full 2½ in. The overall dimensions of the struts were similar to the previous series, and they each had nine battens. Unlike the previous series, however, the channels were hot rolled instead of cold pressed; the cross-sectional area was reduced by 4 per cent. The failing loads were 5·50 and 5·40 tons

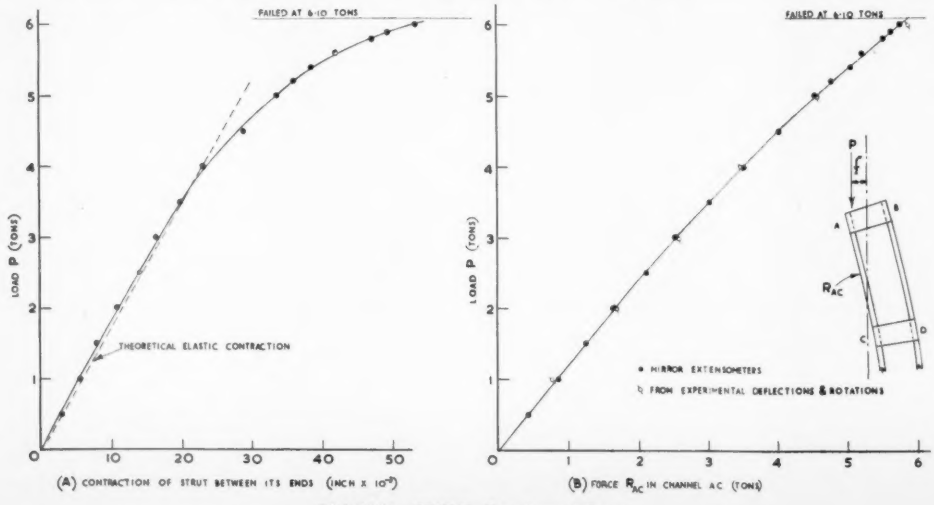
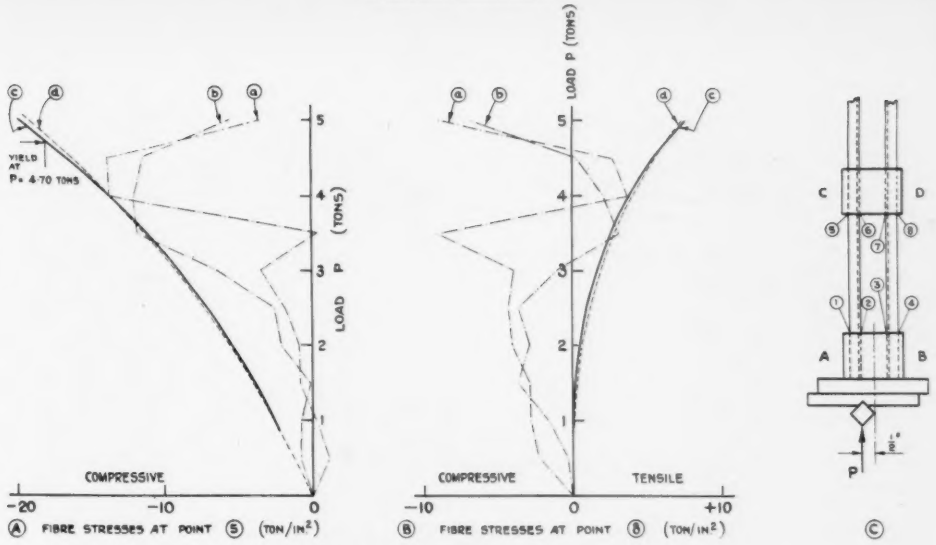


PLATE 33.—9B½E67. Experimental Curves.



Curve (*a*).—Calculated from Experimental deflections and rotations.
Curve (*b*).—Calculated from smoothed experimental curves.
Curve (*c*).—Calculated from Experimental deflections and rotations assuming four equal end moments.
Curve (*d*).—Theoretical curve from elastic analysis.

PLATE 35.—9B½E67. Experimental Curves.

(corresponding to 5·74 and 5·63 tons with the full cross-section). From the smoothed curves in Plate 43a, the collapse loads for the resultant eccentricities should have been 5·92 and 5·82 tons respectively, i.e. 3 per cent. higher than observed. It is thought that this small difference is due mainly to the fact that the joints were not so stiff with the tack as with the full welds, a slight rotational slip reducing the collapse load. There were no cracks in the welds after failure.

Two tests were performed to find Young's modulus using a 10-ton Avery machine and 2 in. mirror extensometers. The resulting values were 13340 and 12850, showing that the value of 13000 tons per sq.in. used in all elastic calculations was reasonable.

Tests were made on rectangular cross-section specimens cut from the channels to find the yield stress of the material. The specimens were tested in the Quinney autographic machine. The results are given in Plate 47, and were analysed statistically; this showed that there were no significant differences between the various batches of channels.

A test of a single joint was carried out to discover whether relative rotation (slip) was occurring between the channel and the batten. Some slip was observed and the relation adopted from the experimental results was, Slip = 0·0058 by (applied moment).

The apparatus used for testing the battened struts had shown itself to be very suitable and did not suffer from any inherent defects. The channel sections chosen gave a little trouble in the welding procedure, but conform to practical design. The experimental work was deficient in that only one length of specimen was used (6 ft.), and that with the exception of the five specimens tested under oblique loading, end shear did not occur. With regard to these five specimens, the percentage shear under ½ in. obliquity was nearly 1½. All collapse loads were greater than the corresponding purely eccentric struts (10 per cent. increase for the 5 batten up to 28 per cent. for the 9 batten).

It is interesting to compare the behaviour of the 9-batten strut with the rules laid down for solid columns in B.S.S. 449. The slenderness ratio was 87, and B.S.S. 449 gives the collapse load of a solid column of this slenderness ratio and the same cross-sectional area as 8·93 tons at a fictitious initial curvature of 0·003 by 87 = 0·261 in. From Plate 43, the collapse load for a 9-batten column at this eccentricity is 7·30 tons, i.e. an 18 per cent. reduction in strength.

The unsupported length of the channels was important, and it seems that the upper limit was reached with 9 battens when the slenderness ratio was 50. Thus it would be uneconomical to use battened columns when the unsupported length of the main member has a slenderness ratio less than this value.

The amount of welding required at the joints is not great, as can be seen from the two tests on tack-welded specimens. Even these latter allowed very little relative rotation. Such rotation would reduce the collapse load considerably as a small relative slip has a large influence on the deflections and rotations of the battens; this trouble is particularly marked when riveted joints are used.

For further investigations the following lines of research would be interesting:

(1) Tests should be carried out on longer columns to give elastic instability without plastic failure of the members. Shorter columns will give collapse due to compressive breakdown of the material.
(2) Specimens of different cross-section should be used, and work on different shapes and sizes can be undertaken.
(3) The influence of shear on the rotational slip at the joints should be investigated.
(4) All specimens tested had free ends. The effect of end restraint should be investigated.
(5) Tests on full-scale columns would check the method of design used for smaller specimens.

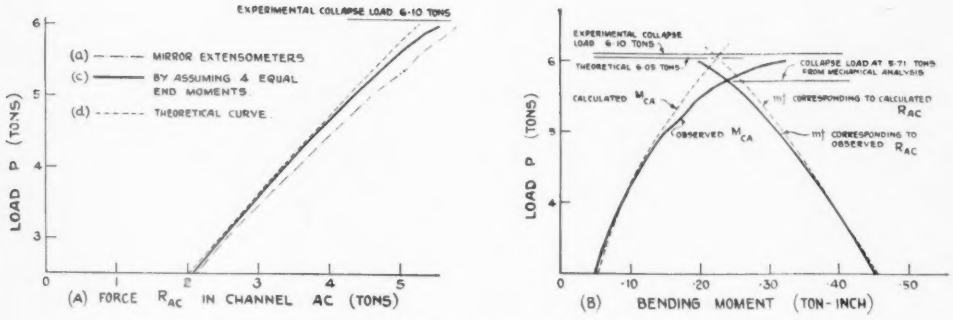

EXPERIMENTAL COLLAPSE LOAD 6·10 TONS
(a) MIRROR EXTENSOMETERS
(c) BY ASSUMING 4 EQUAL END MOMENTS
(d) THEORETICAL CURVE
LOAD P (TONS)
(A) FORCE R_{AC} IN CHANNEL AC (TONS)
EXPERIMENTAL COLLAPSE LOAD 6·10 TONS
THEORETICAL 6·05 TONS
COLLAPSE LOAD AT 5·71 TONS FROM MECHANICAL ANALYSIS
CALCULATED M_{CA}
OBSERVED M_{CA}
m CORRESPONDING TO CALCULATED R_{AC}
m CORRESPONDING TO OBSERVED R_{AC}
LOAD P (TONS)
(B) BENDING MOMENT (TON-INCH)

PLATE 36.—9B½E67. Mechanical Analysis.

Strut Specimen No.	Channel Nos. West	Channel Nos. East	Twist (ins.)	Length over Milled Ends (ins.)	End Fittings	Length between Knife Edges	Date Tested	Collapse Load Tons	Initial Curvature at Panel Points U_2	U_3	U_4	U_5	U_6	U_7	U_8		
5B½01	12	13	—	72 — ⅛	S	75·493	5-2-46	4·057	−·0225	−·0975	−·0775						
6B½02	14	15	—	72 — 3/32	S	75·524	12-2-46	5·6204	+·0225	+·0325	+·0300					qr	
8B½03	17*	16	—	72 — ⅛	S	75·493	25-2-46	7·4137	+·10	+·0475	+·0300					qr	
7B½04	21	20	+1·0	72 — ⅛	S	75·493	21-3-46	6·6544	+·020	+·0125	+·010					qr	
9B½05	23	22*	+·60	72 — ⅛	S	75·493	23-3-46	9·2143	+·0325	+·0325	+·025					qr	
5B½E6	18*	19*	+·80	72 — 3/32	S	75·524	25-3-46	3·7267	+·025	+·020	+·025						ts
7B½E7	26	27	+·50	72 — ⅛	S	75·493	26-3-46	5·0962	+·0675	+·065	+·0275					qr	ts
9B½E8	29*	28*	+·40	72 — ⅛	S	75·493	27-3-46	5·7640	+·0225	+·0875	+·075					qr	
5B0E9	24	25	+·80	72 — ⅛	S	75·493	28-3-46	4·3727	+·0275	+·070	+·0675						
6B½E10	38	37	+·10	72 — 1/16	S	75·556	31-5-46	4·5390	+·0175	+·05	+·0625	+·0275					ts
6B0E11	40	39	+·30	72 — 5/64	S	75·540	4-6-46	5·9532	+·02	+·0462	+·055	+·035					
6B½E12	42	41	+·36	72 — ⅛	S	75·493	7-6-46	5·0628	+·0262	+·0738	+·0575	+·0338					
6B½E13	44	43	+·60	72 — 1/16	S	75·556	11-6-46	4·1376	+·0308	+·0288	+·025	+·010					
8B½E14	45	46	0	72 — ⅛	S	75·493	17-7-46	6·2112	−·0067	−·0102	+·0076	+·0104	+·0004	−·0098		m	
8B½E15	47	48	+·60	72 — ⅛	S	75·493	16-8-46	6·6433	+·0416	+·0921	+·0750	+·0478	+·0279	+·0064		m	
8B0E16	49*	50*	+1·20	72 — 1/32	S	75·587	19-8-46	8·0554	+·0528	+·0816	+·0740	+·0499	+·0330	+·0284		m	ts
8B½E17	51	52	+1·50	72 — 3/32	S	75·524	20-8-46	4·6416	−·0084	+·0842	+·1376	+·1887	+·2061	+·1020		m	
7B0E18	54*	53	+1·25	72 — ⅛	S	75·493	9-7-46	7·7650	+·0192	+·0357	+·0626	+·0578	+·0550			m	
7B½E19	56	55	+1·30	72 — ⅛	S	75·493	10-7-46	6·2019	+·0256	+·0305	+·0260	+·0414	+·0116			m	
7B½E20	58*	57*	+1·40	72 — 3/32	S	75·524	22-8-46	4·6695	+·0164	+·0246	+·0520	+·0182	+·0043			m	
5B½E21	59*	60	+·75	72 — ⅛	S	75·493	1-7-46	4·0778	+·0250	+·0362	+·0312						
5B½E22	61*	62	+1·40	72 — 1/16	S	75·556	9-9-46	3·1699	+·0240	+·0662	+·0572					m	
9B0E23	63	64*	+1·20	72 — ⅛	S	75·493	15-7-46	10·5519	+·0176	+·0209	+·0121	−·0032	−·0184	−·0179	−·0414	m	
9B½E24	65	66	+1·40	72 — 1/16	S	75·556	10-9-46	5·6470	+·0252	+·0278	+·0186	−·0190	+·0198	+·0176	+·0120	m	ts
9B½E25	68	67	+1·50	72 — 3/32	S	75·524	12-7-46	6·9682	+·0461	+·0694	+·0823	+·0423	+·0802	+·0458	+·0494	m	
9B½E26	69	70	0	72 — 3/32	DR	76·878	9-12-46	5·4348	+·0496	+·0589	+·0610	+·0678	+·0624	+·0624	+·0337	m	
5B½E27	72	71	−·05	72 — 1/128	DR	76·964	12-12-46	3·6024	+·0193	+·0119	+·0178					m	
7B½E28	74	73	−·10	0	DR	76·972	6-12-46	4·9270	+·0062	+·0178	+·0354	+·0174	+·0205			m	
9B½E29	75	76	−·22	72 — 3/32	DR	76·878	10-12-46	6·1710	+·0430	+·0535	+·0579	+·0410	+·0360	+·0284	+·0172	m	
7B½E30	90*	89	+·40	72 + 1/64	DR	76·988	14-12-46	5·1579	+·0201	+·0224	+·0321	+·0447	+·0122			m	ts
7B½E31	92*	91	−·20	72 + 3/32	DR	77·066	9-1-47	6·0340	+·0338	+·0591	+·0634	+·0053	+·0123			m	
7B0E32	94*	93*	+·30	72 + 1/32	DR	77·003	10-1-47	7·6170	+·0269	+·0469	+·0515	0	+·0086			m	
7B½E33	95	96	−·15	72 — 1/64	DR	76·956	19-3-47	5·3491	+·0201	+·0093	+·0137	+·0282	+·0110			m	
9B½E34	97*	98*	+·10	72 + 1/64	DR	76·988	20-12-46	7·1742	−·0009	+·0031	−·0051	−·0064	−·0134	−·0088	+·0056	m	ts
9B0E35	99*	100*	−·15	72 + 1/64	DR	76·988	6-2-47	8·9962	+·0384	+·0562	+·0676	+·0623	+·0635	+·0569	+·0390	m	

PLATE 38.—Complete List of Strut Specimens Tested

Strut Specimen No.	Channel Nos. West	Channel Nos. East	Twist (ins.)	Length over Milled Ends (ins.)	End Fittings	Length between Knife Edges	Date Tested	Collapse Load Tons	Initial Curvature at Panel Points U_2	U_3	U_4	U_5	U_6	U_7	U_8		
9B0E36	101	102	−·20	72+1/64	DR	76·988	8-2-47	8·5026	+·0296	+·0534	+·0788	+·0824	+·0888	+·0868	+·0514	m	
8B¼E37	103	107	+·20	72+1/32	DR	77·003	25-1-47	4·6281	+·0255	+·0654	+·0870	+·0902	+·0820	+·0562		m	ts
8B½E38	104	108	+·30	0	DR	76·972	28-1-47	5·6472	−·0080	+·0277	+·0365	+·0381	+·0280	−·0116		m	
8B¼E39	105	106*	+·60	72+1/64	DR	76·988	30-1-47	6·1516	+·0496	+·0870	+·1084	+·1095	+·0996	+·0628		m	
5B¾E40	120	119	−·50	72+1/64	DR	76·988	13-1-47	3·2665	−·0020	+·0183	+·0290					m	
5B¼E41	122	121	−·30	72−1/64	DR	76·956	15-1-47	3·1717	+·1080	+·1330	+·0998					m	
5B¼E42	126	125	+·40	0	DR	76·972	15-1-47	3·7702	+·0416	+·0746	+·0244					m	ts
5B0E43	127	128	−·10	0	DR	76·972	16-1-47	4·9837	−·0027	+·0182	−·0112					m	
6B¾E44	110	109	−·15	0	DR	76·972	17-1-47	4·2296	−·0084	+·0023	+·0120	+·0128				m	
6B½E45	111	112	+·35	72+1/64	DR	76·988	18-1-47	4·1078	+·0743	+·0866	+·0628	+·0418				m	
6B¼E46	113	114	+·20	72−1/64	DR	76·956	20-1-47	5·0114	+·0398	+·0406	+·0516	+·0262				m	
6B0E47	115	116	−·25	0	DR	76·972	23-1-47	5·7655	+·0441	+·0369	+·0473	+·0457				m	ts
6B0E48	117	118	−·60	72+1/64	DR	76·988	27-9-47	6·4301	+·0258	+·0300	+·0140	+·0042				m	
5B¼E49	130	129*	+·10	72 .02	DR	76·952	24-9-47	3·2637	+·0278	+·0916	+·0842					m	
5B E50	132*	131*	+·48	0	—	—	—	—	+·0985	+·1282	+·0616					m	
5B0E51	134*	133*	+·10	0	DR	76·972	25-9-47	4·9467	−·0090	+·0057	+·0107					m	
5B½E52	135	136	+·14	0	DR	76·972	24-9-47	3·9817	+·0606	+·0282	+·0504					m	
6B½E53	137*	138*	+·10	72+·01	DR	76·982	24-9-47	5·10	+·0499	+·0193	−·0074	−·0106				m	
6B½E54	139*	140*	+·36	72+·02	DR	76·992	23-9-47	4·3952	+·0388	+·0490	+·0332	+·0083				m	
6B¾E55	141*	142*	+·37	72+·03	DR	77·002	30-9-47	3·9844	+·0388	+·0670	+·0334	+·0378				m	
7B0E56	143	144	−·12	72+·03	DR	77·002	30-9-47	8·3606	+·0217	+·0078	+·0064	+·0342	−·0019			m	
7B¼E57	146	145	+·38	72 ·04	DR	76·932	25-9-47	5·9938	+·0278	+·0396	+·0228	−·0190	−·0250			m	
7B¾E58	148	147	+·14	72+·01	DR	76·982	2-10-47	4·7707	−·0171	−·0113	+·0246	+·0219	+·0068			m	
7B E59	150	149	+·13	72+·02	—	—	—	—	+·0358	+·0816	+·0644	−·0078	+·0232			m	
8B¼E60	152*	151*	+·50	72+·02	DR	76·992	18-8-47	6·40	+·0448	+·0884	+·0854	+·0726	+·0274	+·0034		m	
8B¼E61	153*	154*	+·23	72+·02	DR	76·992	25-7-47	5·60	+·0390	+·0530	+·0679	+·0402	+·0097	+·0085		m	
8B½E62	155	156	−·65	0	DR	76·972	6-8-47	4·70	+·0605	+·0981	+·1266	+·1314	+·1138	+·0706		m	
8B0E63	157*	158*	+·37	72+·03	DR	77·002	26-9-47	8·40	+·0525	+·0729	+·0840	+·0508	+·0222	+·0105		m	
8B0E64	160*	159*	−·10	72+·02	DR	76·992	26-9-47	8·90	+·0080	+·0146	+·0108	+·0282	+·0250	+·0200		m	
9B¼E65	161	162	+·40	72+·01	DR	76·982	19-7-47	6·90	+·0322	+·0531	+·0515	+·0506	+·0497	+·0516	+·0274	m	
9B0E66	163*	164*	−·12	72+·01	DR	76·982	23-7-47	9·60	+·0110	+·0204	+·0362	+·0302	+·0366	+·0377	+·0322	m	
9B¼E67	166*	165*	+·06	72+·03	DR	77·002	11-7-47	6·10	−·0034	−·0037	−·0051	−·0113	−·0014	+·0222	+·0236	m	
9B½E68	168	167	−·01	72+·03	DR	77·002	15-7-47	5·10	+·0150	+·0484	+·0652	+·0862	+·1190	+·0870	+·0428	m	
S9B½E69	169	169	−·03	72−·22	D	76·752	19-8-47	5·50	—	—	—	+·10					
S9B½E70	170	170	0	72−·09	DR	76·882	18-9-47	5·40	—	—	—	+·125					

PLATE 39.—Complete List of Strut Specimens Tested

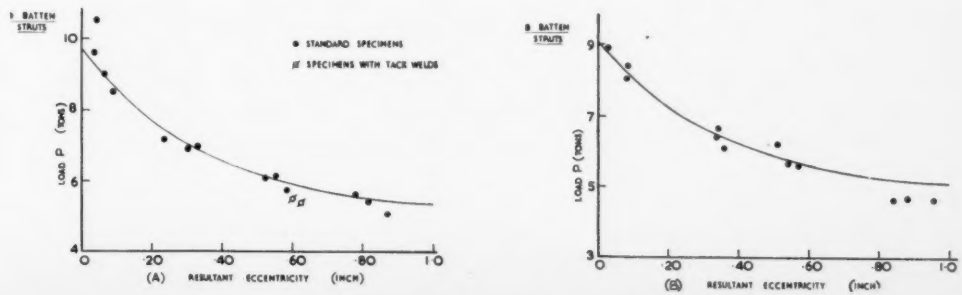


PLATE 43.—Experimental collapse loads.

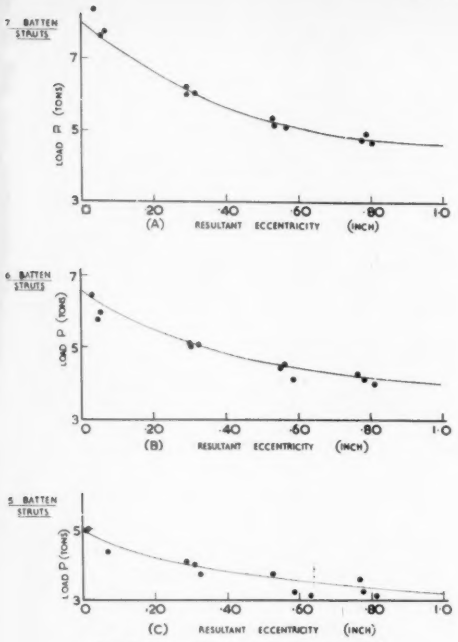
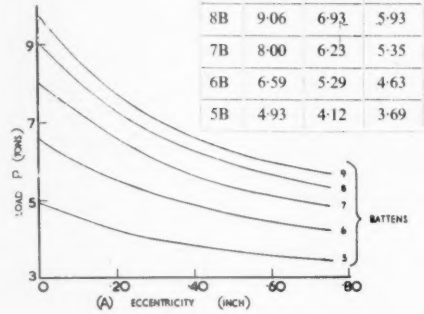


PLATE 44.—Experimental collapse loads.

	O.E.	¼ E.	½ E.	¾ E.
9B	9·73	7·36	6·29	5·60
8B	9·06	6·93	5·93	5·32
7B	8·00	6·23	5·35	4·78
6B	6·59	5·29	4·63	4·16
5B	4·93	4·12	3·69	3·36



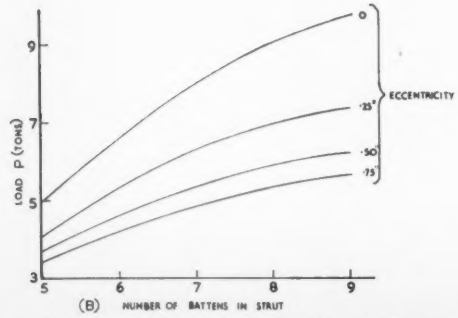


PLATE 45.—Experimental collapse loads—adopted values.

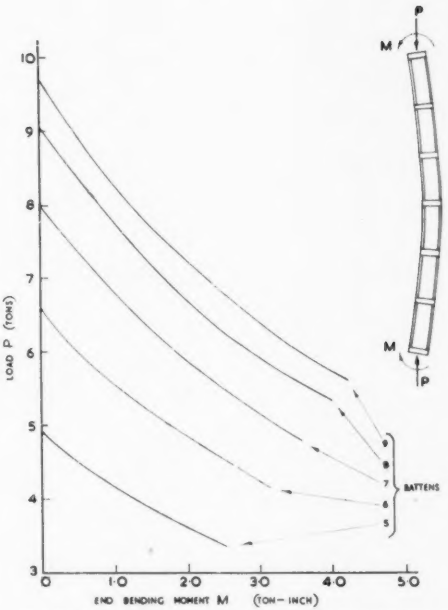


PLATE 46.—Experimental collapse loads—adopted values.

Date Tested	Channel No.	Per cent. Elongation	Yield Stress Tons per sq.in.	Maximum Stress Tons per sq.in.
Feb., Mar. 1946	R.B. 11/1	30	19·14	26·35
	11/2	24	17·88	24·56
	30/1	26	19·96	26·61
	30/2	26	18·42	25·71
Nov. 1946	18	26	19·13	25·30
	19	26	20·01	25·77
	26	24	17·94	24·83
	27	25	19·82	26·83
Nov. 1946	37	25	19·11	25·06
	38	25	17·96	24·96
	50	26	18·72	25·26
	65	26	18·94	25·59
	66	26	18·62	25·40
Oct. 1947	89	20	19·84	25·44
	98	27	19·93	25·35
	107	26	18·17	24·71
	116	28	19·26	24·19
	125	25	19·70	25·09
	Average	25·6	19·03	25·39

PLATE 47.—Tension Tests

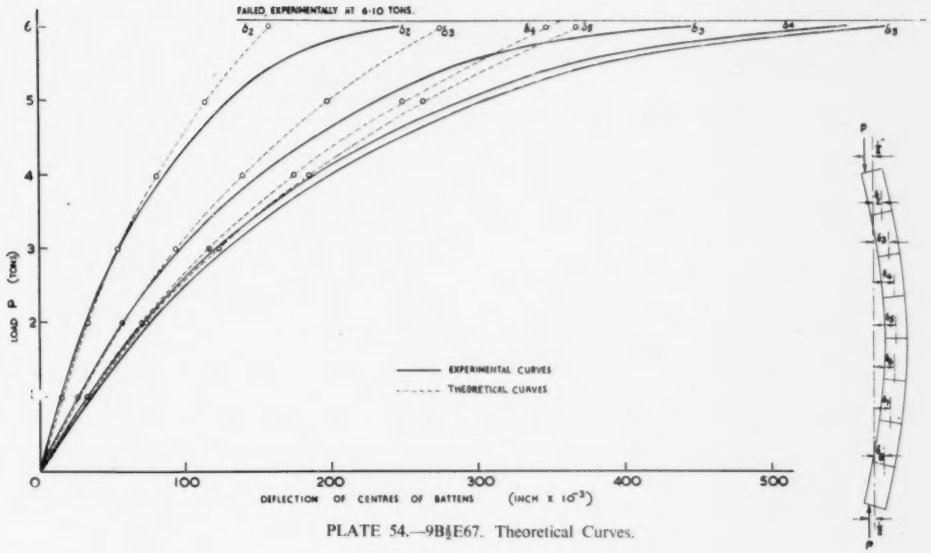


PLATE 54.—9B½E67. Theoretical Curves.

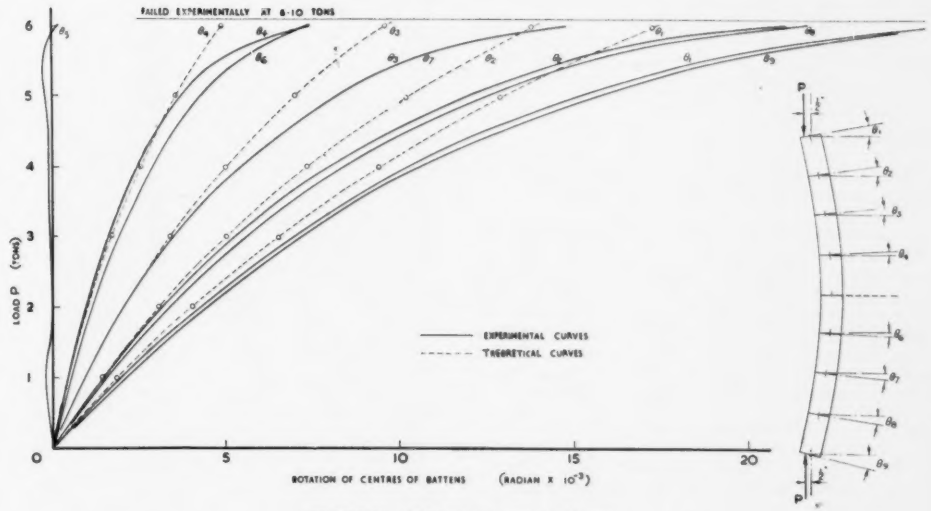


PLATE 55.—9B½E67. Theoretical Curves.

THEORETICAL WORK

The possibilities of using a relaxation process for investigating the elastic behaviour of a column were first investigated. However, the process is laborious and convergence was slow, and the method was abandoned in favour of the direct solution of a set of simultaneous equations.

For a 9-batten strut, for example, eight simultaneous equations can be set up for eight unknowns according to certain assumptions; it happens that these equations can be solved very readily, giving information as to the state of any portion of the strut. The results are shown as curves superimposed on the experimental results in Plates 54, 55, 56 and 57 for strut 9B½E67.

As mentioned above, curves of plastic moment have been calculated for various axial loads in the channel, assuming the lower yield stress of the material to be 18 tons per sq.in. (Upper yield stress was ignored.) The channel was assumed to have rectangular web and flanges. With the notation shown there, the curves are plotted in plates 59 and 60. The shape of the curves in Plate 60 is rather extraordinary, maximum moments occurring not when the axial load is zero but at definite values.

In order to find the theoretical collapse load of any strut the following procedure is used. For any value of P the calculated moment M_{CA} is known and P may be plotted against this moment. But for any value of P the value of the force R_{AC} is known, and the value of the full plastic moment corresponding to this force can also be plotted against P. The intersection of these two curves (Plate 36) gives the collapse load. This analysis is based on the assumptions that though a portion of the free channel has yielded the flexibility is not increased, and that when one of the four ends of the channels in the end panel reaches the full plastic moment, the strut collapses. This gives a value for the collapse load which is in general very slightly less than the experimental value.

CONCLUSIONS

The following general conclusions can be drawn from the experimental and theoretical work:

(*a*) The results of the elastic theory showed satisfactory agreement with the observed deflections and rotations. Creep was noticed well below the collapse load, indicating that yield had been reached in some section of the strut; none of the specimens failed elastically. The mode of collapse was usually plastic failure of the unsupported length of the channels in the end panel, both of which were bent in double curvature. The collapse load calculated by an approximate plastic theory agreed well with the experimental value.

Another mode of failure was encountered if the container at the end of the loading lever was restrained in its descent after the final increment had been added. This made the strut fail by plastic instability in single curvature bending of one channel in the centre panel.

(*b*) Loads were applied by means of the two knife edges at each end, giving, in effect, a point load. Struts subjected to oblique loading were stronger than those with the eccentricities on the same side of the axis, and the collapse load increased as the eccentricity was reduced.

Nearly all practical connections are rigid or semi-rigid. From the work of Prof. J. F. Baker and Dr. J. W. Roderick[33] on solid section struts with restrained ends, it may be inferred that a battened column with restrained ends would carry considerably higher collapse loads than those with free end conditions.

(*c*) From the results of these tests, it would seem that the 9-batten strut nearly reached the limit of efficiency (*see* Plate 45), and that it would be uneconomical to increase further the number of battens. For this maximum number of battens, the unsupported main member had a slenderness ratio of about 50.

The panel length was constant in each strut specimen. By a judicious spacing of battens, it would be possible to increase the collapse load slightly. This is not recommended in practice as calculations would become involved, and because errors might be made in fabrication. It might also be possible to increase the strength by increasing the length of the end battens.

(*d*) The amount of welding required at a joint is small if proper attention is paid to design. It was shown that a rotational slip in the joints affected the collapse load of a strut.

(*e*) In specifications for riveted construction latticing was recommended in preference to battening, presumably because of its greater rigidity. In some cases this preference amounted to prohibition. However, with the introduction of welding there is no reason why battened construction cannot be made as rigid as latticing and provided a satisfactory method of design can be evolved due account of this should be taken in future specifications.

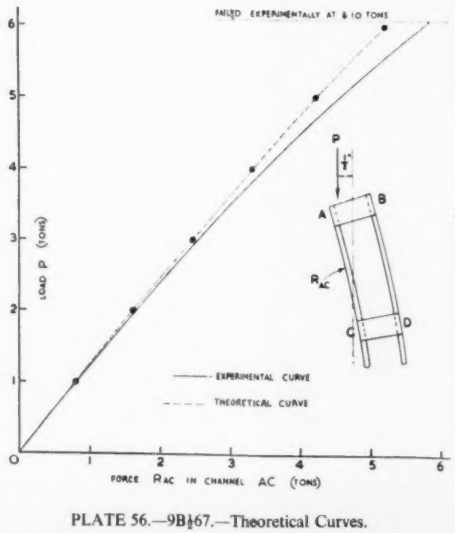


PLATE 56.—9B½67.—Theoretical Curves.

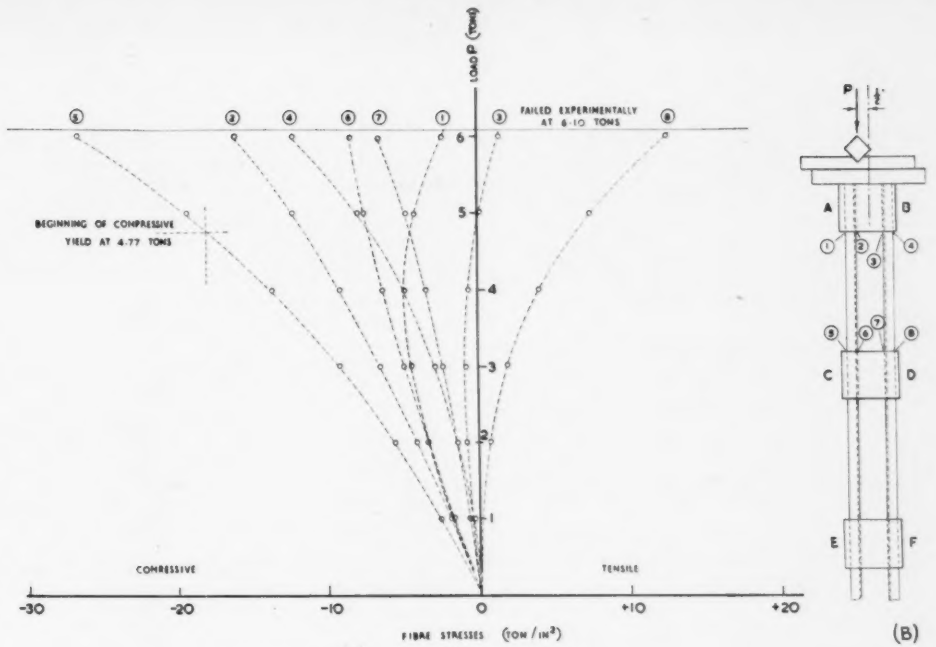


PLATE 57.—9B½E67. Theoretical Curves.

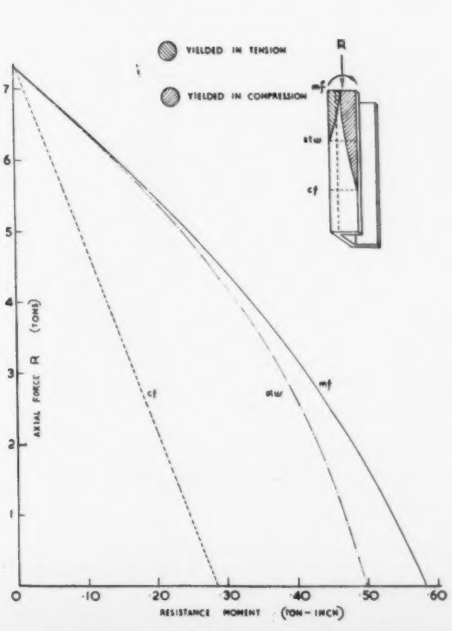


PLATE 59.—Resistance moments of channel section.

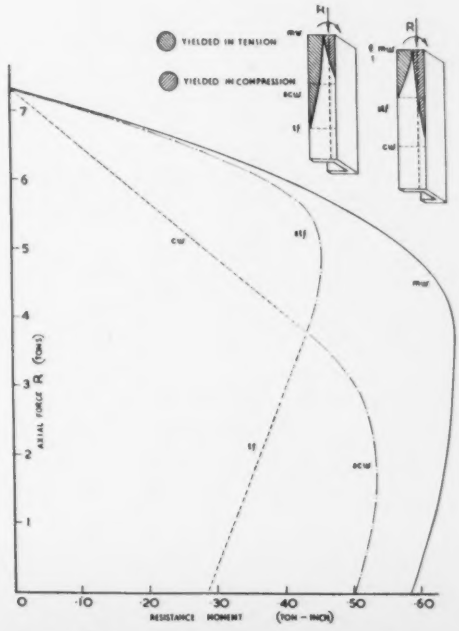


PLATE 60.—Resistance moments of channel section.

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R71

DEVELOPING A WELDABLE HIGH TENSILE STEEL FROM 18-LB. H.F. MELTS

This report was first issued to Members of the British Welding Research Association as a Confidential Document in November, 1950.

SUMMARY

This report covers the preliminary work of the FM.8 Committee of the British Welding Research Association in their effort to develop a weldable high tensile steel having a 0·2 per cent. proof stress of 30 tons. per sq.in. The report discusses the possibility of an 18 lb. high frequency induction furnace melt providing sufficient material for a modification of the "Reeve" fillet weld cracking test. Having established the suitability of using these small experimental melts, the determination of weldability, steel-making technique and the examination of the mechanical properties of the steels were standardised by using one steel from the proposed range of compositions to determine a satisfactory procedure.

INTRODUCTION

This research was carried out at the instigation and under the direction of the FM.8 Committee of the British Welding Research Association. This committee, which was formed to develop higher strength weldable structural steels, decided that there was insufficient known about the effects upon weldability of systematic variations of the various elements in multiple alloy steels. It was generally thought at the time that multiple alloy steels gave the best combination of weldability and mechanical properties.

This work was undertaken in order to determine the combination of manganese, nickel and chromium in manganese-nickel-chromium-molybdenum steels which gave the best combination of weldability and mechanical properties.

The series of steels proposed numbered twenty-seven, there being three levels of alloy content for each of the elements manganese, nickel and chromium. It was well known that carbon had an adverse effect on weldability, so that throughout the series the amount of this element was maintained constant at a low value. The element molybdenum was included in order to maintain a high yield point, but the systematic variation of four elements would have made the series of steels too large, so that molybdenum content was also maintained constant. Because large amounts of molybdenum would be undesirable for economic reasons in a production steel the content was fixed at a low value.

In addition to the main series, four copper containing manganese-nickel-chromium-molybdenum steels were included because it was suggested that copper might improve the yield stress without impairing weldability.

Nominal Compositions of Proposed Steels

No.	C per cent.	Mn per cent.	Cr per cent.	Ni per cent.	Mo per cent.	C. Equivalent per cent.
1	0·15	0·8	0·2	0·5	0·25	0·39*
2	0·15	1·2	0·2	0·5	0·25	0·46
3	0·15	1·6	0·2	0·5	0·25	0·53
4	0·15	0·8	0·2	1·0	0·25	0·43
5	0·15	1·2	0·2	1·0	0·25	0·50
6	0·15	1·6	0·2	1·0	0·25	0·57
7	0·15	0·8	0·2	1·5	0·25	0·46
8	0·15	1·2	0·2	1·5	0·25	0·53
9	0·15	1·6	0·2	1·5	0·25	0·60
10	0·15	0·8	0·6	0·5	0·25	0·47
11	0·15	1·2	0·6	0·5	0·25	0·54
12	0·15	1·6	0·6	0·5	0·25	0·61
13	0·15	0·8	0·6	1·0	0·25	0·51
14	0·15	1·2	0·6	1·0	0·25	0·58
15	0·15	1·6	0·6	1·0	0·25	0·65
16	0·15	0·8	0·6	1·5	0·25	0·54
17	0·15	1·2	0·6	1·5	0·25	0·61
18	0·15	1·6	0·6	1·5	0·25	0·68*
19	0·15	0·8	1·0	0·5	0·25	0·55
20	0·15	1·2	1·0	0·5	0·25	0·62
21	0·15	1·6	1·0	0·5	0·25	0·69*
22	0·15	0·8	1·0	1·0	0·25	0·59
23	0·15	1·2	1·0	1·0	0·25	0·66*
24	0·15	1·6	1·0	1·0	0·25	0·73*
25	0·15	0·8	1·0	1·5	0·25	0·62
26	0·15	1·2	1·0	1·5	0·25	0·69*
27	0·15	1·6	1·0	1·5	0·25	0·76*

* =C. equivalent below or above the range 0·45-0·65 per cent.

In addition steels containing copper and nickel:

No.	C per cent.	Mn per cent.	Cr per cent.	Ni per cent.	Mo per cent.	Cu per cent.
28	0·15	0·8	0·2	1·0	0·25	1·0
29	0·15	0·8	0·2	1·5	0·25	1·0
30	0·15	0·8	0·6	1·0	0·25	1·0
31	0·15	0·8	0·6	1·5	0·25	1·0

It was thought desirable that sufficient material should be avilable for two test welds to be made when using a modification of the "Reeve" fillet weld cracking test. In order to determine whether an 18 lb. high frequency induction melt

would give sufficient material for this purpose, Colvilles Ltd. undertook some preliminary work and submitted the following report to the Committee.

Ingot dimensions: Top 3½ in. diameter.
Base 2⅞ in. diameter.
Overall length 10 in.

This was forged to a strip approximately 20 in. long by 6 in. wide by ½ in. thick. The strip was normalised and thereafter cut to give two plates necessary for a modified form of Reeve test, viz. a base plate 12 in. by 6 in. from the *top* portion of ingot, and a top plate 5 in. by 5 in. from the *base* of ingot. In addition a strip 5 in. by 1 in. was obtained for a tensile test.

Two modified Reeve test plates were bolted to a 2-in. steel slab (Fig. 1), and after bolting up tight with ⅞ in. diameter bolts, sides (*a*) and (*c*) of the top plate were anchored to the base plate by fillet welds. When the specimen had cooled to room temperature the test fillet weld was laid on side (*b*) using 5/32 in. diameter electrode. After cooling down again to room temperature a second test fillet was laid on side (*d*) with ¼ in. diameter electrode. Since ample material was available for the test, it would appear from these experiments that 18 lb. high frequency melts are adequate for this purpose, at least for the initial survey; selected compositions can then be dealt with on a larger scale at a later stage.

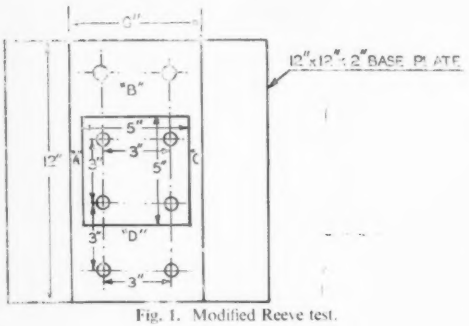


Fig. 1. Modified Reeve test.

As a result of this report the FM.8 Committee agreed that the tests should be undertaken on the experimental series of steels made by the high frequency induction process and cast in 18 lb. ingots.

In order to arrive at a standard procedure of manufacture it was decided that in the first instance Steel No. 9 should be made by each company and tested for weldability.

The following companies offered to produce the steels after the standardised procedure had been agreed upon.

United Steel Companies Ltd. ..	Steels 1-10
Colvilles Ltd.	Steels 11-21
Mond Nickel Co. Ltd.	Steels 22-31

INVESTIGATIONS—PART I

In order to compare the results from the initial laboratory tests on one steel of the series, reports are appended from the three companies who had agreed to cast the steels.

(A) EXAMINATION OF THE WELDABILITY OF LOW ALLOY STEEL No. 9

Submitted by The Mond Nickel Co. Ltd.

In order to determine what degree of reproducibility of welding properties could be obtained in steels made and tested by individual investigators, three laboratories undertook each to prepare and test one 18 lb. high frequency melt to the following nominal composition:

	Composition per cent.
Carbon	0·13 to 0·17
Silicon	0·20 „ 0·25
Manganese	1·4 „ 1·8
Chromium	0·15 „ 0·25
Nickel	1·45 „ 1·55
Molybdenum	0·22 „ 0·28
Sulphur	0·035
Phosphorus	0·035

This type of steel, referred to as No. 9 of the series, was selected for this inter-laboratory check as it was considered that the weldability of such a steel would be critical.

Melting

The raw materials and the melting procedure used in making the steel were as agreed between the collaborating laboratories, using Lowmoor iron as the base of the furnace charge. The casting temperature was 1580 deg. C. and the ingot was given the laboratory mark JEV.

Chemical Analysis

From the base of the ingot a sample for chemical analysis was taken which gave the following results:

	Composition per cent.
Carbon	0·145
Silicon	0·25
Manganese	1·63
Chromium	0·17
Nickel	1·5
Molybdenum	0·24
Sulphur	0·31
Phosphorus	0·037

Preparation of Test Plates

The ingot was upset to give a billet 10 in. by 4 in. by 1¼ in., and this was forged to give a plate 9/16 in. thick by 6 in. wide; the forging temperature for both operations was 1100 deg. C.

The plate was normalised at 900 deg. C. for half-an-hour and air cooled; subsequently it was cut to suit the modified Reeve test (Fig. 1) to give a top plate 5 in. square and a base plate approximately 6 in. by 11½ in. The plates were then surface ground on both faces to give test coupons ½ in. thick.

Mechanical Tests

A tensile test piece (0·252 in. diameter by 2½ in. gauge length) was taken from the plate before welding, and an Izod test piece (0·45 in. diameter) was cut from the top test plate after welding. The results obtained were:

Maximum Stress Tons/sq.in.	0·2 % Proof Stress Tons/sq.in.	0·5 % Proof Stress Tons/sq.in.	Elongation % on 2 in.	Elongation % $4\sqrt{\text{area}}$	Reduction of Area %	Izod ft. lbs.
56·7	33·5	39·6	15·5	25·8	52·0	6, 6, 12

Welding Test

The welding test consisted of the modified Reeve test using a 5-in. square top plate placed centrally on a base plate 12 in. by 6 in., eight ⅞ in. diameter bolts being used to fix the test plates rigidly to a mild steel bed plate, 2 in. thick. The side anchor runs were made with 4 s.w.g. Fastex electrodes and the whole set-up was allowed to cool; any slack bolts were then tightened and the first test run was laid down. This run was made using a 10 s.w.g. Fastex 5 electrode, and the set-up was again allowed to cool and the bolts tightened before the second test run was laid down, using a 6 s.w.g. Fastex 5 electrode.

The welding details were:

Electrode	Gauge	Welding Voltage	Current amps.	Time for 5 in. Run	Length of Electrode Used
Fastex 5	10 s.w.g.	20	115	50 secs.	9 in.
Fastex 5	6 ,,	19	205	52 ,,	8 ,,

Bed plate temperature before welding – 21·5 deg. C.

The steel gave no trouble in the welding operation, and good fillets were obtained. The set-up was allowed to cool, and then three sections were cut from each of the test runs and polished for micro-examination and hardness surveys.

Microscopical Examination

Cracking was present in the vertical leg of all six specimens examined. The cracking had occurred in the plate, parallel to the weld metal/plate interface, and extended in all cases for 90 to 95 per cent. of the length of the vertical leg.

Hardness Surveys

A Diamond Pyramid Hardness survey (10 kg. load) was carried out on one of the sections from each test weld. The results are given below:

Electrode Size	Average Weld Metal Hardness D.P.N.	Leg Length V. in.	Leg Length H. in.	Approx. Area of Fillet	Maximum Weld Zone Hardness D.P.N.	Average Weld Zone Hardness D.P.N.
10 s.w.g.	249	0·180	0·280	0·025	433	422
6 ,,	235	0·325	0·325	0·052	425	419

The fillet areas were calculated from the formula $\frac{V \times H}{2}$ where V is the length of the vertical leg and H the length of the horizontal leg.

Discussions of Results

The present results show cracking in steel No. 9 when made from a Lowmoor iron charge. One query which arises is whether the hardness in the weld zone would have been quite so high or the cracking tendency present if the test had been carried out without surface grinding of the test plates, which would leave the plates in less intimate thermal contact. A decision as to whether surface grinding is to be employed in future work with this form of test seems necessary.

(B) PREPARATION AND EXAMINATION OF LOW ALLOY STEEL No. 9

Submitted by Colvilles Ltd.

For the purpose of inter-laboratory checks, one steel of the series was selected, and each laboratory undertook to prepare one 18-lb. high frequency cast to the following specification:

	Composition per cent
Carbon	0·13 to 0·17
Manganese	1·4 ,, 1·8
Chromium	0·15 ,, 0·25
Nickel	1·45 ,, 1·55
Molybdenum	0·22 ,, 0·28
Sulphur	0·035
Phosphorus	0·035

This cast was designated HF. 989. A similar charge (cast H.F. 987) was made using the normal scrap in place of the Lowmoor iron. After casting, the ingots were forged to 17/32 in. thick by 6 in. wide plates, using the whole ingot. From the base portion a sample was analysed and the following results obtained:

Cast No.	C %	Si %	S %	P %	Mn %	Ni %
HF. 989 ..	0·15	0·26	0·040	0·035	1·48	1·47
HF. 987 ..	0·14	0·23	0·035	0·040	1·62	1·54

Cast No.	Cr %	Mo %	Cu %	Sn %	N %
HF. 989 ..	0·23	0·26	0·10	0·012	0·0147
HF. 987 ..	0·20	0·25	0·085	0·018	0·0095

After forging, the plates were cut as described by Colvilles Ltd. in a report circulated to the FM.8 Committee.* The pieces were normalised at 900 deg. C. for half-an-hour and air cooled.

*Referred to on page 190*r* of this report.

After this treatment, one surface of the plates was machined to give ½ in. thick specimens, and at the same time ensure one smooth surface for a proper fit-up when bolted to the base plate.

From the small end pieces tensile and impact tests were prepared and the following results obtained:

Dimensions of Tensile Testpiece 0·357 in. diameter by 2 in. gauge length

Cast No.	Maximum Stress Tons per sq.in.	0·2 % P.S. Tons per sq. in.	Reduction of Area %	Elongation % on 2 in.	Izod Impact ft. lbs.
HF. 989	56·7	36·0	45·5	14·5	12, 10, 14 C.
HF. 987	57·0	39·6	47·0	12·0	11, 8, 12 C.

Grain Size: The McQuaid-Ehn grain size of both steels was 3/5.

Welding Tests

The welding tests consisted of a modified Reeve fillet weld test (Fig. 1). The side fillets were made with ¼ in. SA.85 electrodes and the whole set-up allowed to cool. Any slack bolts were tightened at this stage.

The first test fillet was laid with a 10 s.w.g. Fastex 5 electrode. The plates were again allowed to cool, bolts tightened, and the second fillet made with 6 s.w.g. of the same rod. The welding details are given in the following table:

Test No.	Rod	Gauge	Volts	Amps.	Time for 5 in. Run	Length of Rod Used
HF. 989A	Fastex 5	10 s.w.g.	20	125	45 secs.	9 in.
B	,,	6 ,,	22	210	55 ,,	9 ,,
HF. 987A	,,	10 s.w.g.	20	125	50 ,,	9½ ,,
B	,,	6 ,,	22	210	57 ,,	8½ ,,

Temperature of Welding Tests – 22 deg. C.

Neither steel gave trouble in welding, and excellent fillets were obtained. There is close agreement of welding conditions between the two samples. When cold, three micro-sections were cut from each test fillet and examined in the magnetic crack detector.

HF. 989A and B Both crack-free in all three specimens.

HF. 987A and B Cracks in the fusion zone in vertical leg.

The centre specimen of each set of three was polished for micro-examination.

HF. 989A and B were again found to be sound.
HF. 987A showed a crack in the fusion zone of the vertical leg, and micro-cracks in the horizontal leg.
HF. 987B showed a crack in the vertical leg of the fusion zone while the horizontal leg was sound.

Hardness Surveys

Hardness surveys were carried out on all four test welds using 10 kg. load. The fillet area was determined by means of a planimeter and calculated from the formula $\frac{V \times H}{2}$ where V is the length of the vertical leg and H the length of the horizontal leg. These areas, together with carbon equivalent and maximum and mean hardness figures, are given in the following table:

Test No.	Equivalent Carbon %	Leg Length V. (in.)	Leg Length H. (in.)	V × H / 2 (sq. in.)	By planimeter (sq. in.)	Max. H_D/10 kg. Load	Mean H_D/10 kg. Load
HF. 989A	0·602	0·20	0·24	0·024	0·027	417	404
HF. 989B	0·602	0·275	0·35	0·048	0·049	417	404
HF. 987A	0·612	0·175	0·24	0·021	0·027	505	387
HF. 987B	0·612	0·31	0·325	0·053	0·066	390	368

Summary and Conclusions

An experimental cast has been prepared to the specification agreed by the FM.8 Committee, and welding tests carried out using a modified Reeve Test and two welding techniques in the range specified. The results indicate that this particular charge is immune from cracking, even where a small fillet is deposited. A comparable charge using a different melting technique and raw material has also been prepared. The analysis, except for the manganese content, was closely similar, but the behaviour in welding tests is vastly different, both test fillets showing severe cracking in the vertical leg. Careful analyses have been done both gravimetrically and spectrographically on these two casts in an effort to trace any other slight difference, but so far none has been detected.

(C) WELDABILITY TESTS ON LOW ALLOY STEEL No. 9

Submitted by S. Fox & Co. Ltd.

The following records the results of tests carried out on Steel No. 9 of the series, prepared and tested according to a pre-arranged procedure as part of a programme of inter-laboratory checks.

Plate Details

	Composition per cent. C	Mn	Si	S	P	Ni	Cr	Mo
Specification	0·15	1·6	—	0·035	0·035	1·50	0·20	0·25
Cast S.G. 5518	0·14	1·56	0·19	0·028	0·035	1·55	0·15	0·25

Raw materials and melting procedure are given in Table III.

Forging

Top plate forged to 5 in. by 5 in. by $\frac{5}{8}$ in. and machine to 5 in. by 5 in. by $\frac{1}{4}$ in.

Bottom plate forged to 12 in. by 6 in. by 7/16 in. and ground on top face.

Heat Treatment

Normalised at 900 deg. C. for half-an-hour and air cooled.

Mechanical Tests in Normalised Condition

Tensile .. .. 0·0357 in. diameter, 2 in. gauge length
Impact .. .. Standard Round Izod
Maximum stress .. 53·4 tons per sq.in.
Proof stress (per cent.) 0·05 (21·6 tons per sq.in.)
0·1 (26·5 „ „ „)
0·2 (31·2 „ „ „)
Elongation on 2 in. per cent. .. 18
Reduction of area, per cent. .. .. 54·6
Izod impact ft. lbs. 12, 10, 11
Hardness H_B/120 .. 258

Welding Tests

Modified Reeve fillet weld as shown in Fig. 1.

Table I.—Raw Materials, Charges and Melting

Charge	Weight gms.	SG 5617 Time	SG 5618 Time	SG 5619 Time
Lowmoor iron AB40	7414	Power on .. 8.59	Power on .. 9.41	Power on .. 10.17
White iron special	220			
Nickel	117			
Additions—				
75 per cent. Fe-Si	16	9.35	10.11	10.46
Carbon-free Fe-Cr	27	9.36	10.12	10.47
Fe-Mo	22	9.37	10.13	10.48
Fe-S	4½	9.38	10.14	10.49
Law carbon Fe-Mn	180	9.39	10.15	10.50
		Tapped 9.40	Tapped 10.16	Tapped 10.51
		Total time .. 41 mins.	Total time .. 35 mins.	Total time .. 34 mins.
		Temperature, 1610 deg. C.	Temperature, 1600 deg. C.	Temperature, 1600 deg. C.

Analysis of Raw Materials—	C	Mn	Si	S	P	Ni	Cr	Mo	Cu
Lowmoor iron	0·09	0·08	0·025	0·005	0·027	0·045	Trace	0·003	0·05
Nickel	—	—	—	—	—	99	—	—	—
75 per cent. Fe-Si	—	—	75	—	—	—	—	—	—
Carbon-free Fe-Cr (GF445) ..	0·055	—	0·37	—	—	—	72·84	—	—
Fe-Mo (58)	—	—	—	—	—	—	—	71·9	—
Fe-S	—	—	—	36·4	—	—	—	—	—
Low Carbon Fe-Mn	0·12	80·10	2·06	—	0·62	—	—	—	1·81

The welding details were:

Electrode	Gauge	Welding Voltage	Current amps.	Time for 5 in. run	Length of Electrode Used
Metrovick E.H.	10	23	120-130	46 secs.	9·5 in.
Fastex 5	6	21	210	64 secs.	9·25 in.

Metallurgical Examination

(*a*) *Position of Sections.*—These were taken at 1½ in., 2½ in. and 3½ in. from the start of the weld.

(*b*) *Period of Incubation.*—The main saw cuts to remove the test welds were made as soon as the sample had reached room temperature. The sections for metallurgical examination were sawn out after sixteen hours.

(*c*) *Crack Susceptibility.*—All sections were examined by magnetic crack detector and microscopically.

(*d*) *Hardness Surveys.*—Hardness tests were carried out on the centre sections.

The results of the metallurgical examination, including weld sizes and maximum hardness, are given below :—

Test No.	Leg Length V (in.)	Leg Length H (in.)	$\frac{V \times H}{2}$ (sq. in.)	Incidence of Cracking: Magnetic	Incidence of Cracking: Micro	Hardness (10 kg. load): Max.	Hardness (10 kg. load): Av.
10/1	—	—	—	Horizontal leg	Horizontal leg	—	—
10/2	—	—	—	Vertical leg	Vertical leg	429	407
10/3	·25	·20	·025	None	Vertical leg	—	—
6/1	—	—	—	None	None	—	—
6/2	·35	·30	·052	Small in middle of vertical leg	Small in middle of vertical leg	405	372
6/3	—	—	—	None	None	—	—

Summary and Conclusions

A low carbon 1¼ per cent. Mn 1½ per cent. Ni-Cr-Mo steel has been prepared as a high frequency melt and tested for weldability, using a modified form of a Reeve fillet weld test. The results show that the steel is susceptible to cracking under the given conditions of testing and manufacture.

INVESTIGATIONS—PART II

At a meeting of the FM.8 Committee, subsequent to the completion of the previous work, the results obtained by the three laboratories were tabled:

United Steel Companies .. .. Cracks
Mond Nickel Company .. .. Cracks
Colvilles .. .. No cracks

Discussion showed that there had been variations in the testing procedure adopted by the different laboratories, especially regarding heat conductivity between top and bottom plates. In the case of United Steel Companies Ltd. the use of high carbon Fe-Mn eliminated re-phosphorisation with the Fe-P as required by Colvilles. It was decided that each laboratory should repeat its tests, using the following standard procedure:

(*a*) Electrode Moisture. The electrodes to be baked at 110 deg. C. for two hours immediately before use.

(*b*) Electrode Variability. The electrodes to be supplied from one batch by Mond Nickel Co. Ltd.

(*c*) Period of Incubation. The welded test piece to be allowed to stand in the jig overnight before cutting out the sections.

(*d*) Contact between faces. The surfaces in contact to be ground in order to provide good thermal conductivity.

Repeat tests were carried out using the agreed procedure, and complete agreement was obtained in that each report showed alloy steel No. 9 to be susceptible to severe cracking under the testing conditions used. The following report is typical of the results obtained:

REPEAT WELDABILITY TESTS ON LOW ALLOY STEEL No. 9

Submitted by S. Fox & Co. Ltd.

Introduction

The first series of inter-laboratory tests on steel No. 9 did not provide an acceptable measure of agreement and repeat tests were required by the Committee.

Three additional casts have been examined, and the results obtained are recorded herewith:

Plate Details

	C	Mn	Si	S	P	Ni	Cr	Mo
Specification	0·13	1·4	—	0·035	0·035	1·45	0·15	0·22
	0·17	1·8				1·55	0·25	0·28
Cast SG.5617	0·14	1·70	0·20	0·032	0·044	1·54	0·25	0·22
Cast SG.5618	0·15	1·86	0·20	0·032	0·044	1·50	0·23	0·23
Cast SG.5619	0·16	1·73	0·20	0·031	0·042	1·53	0·25	0·22

Raw materials and melting procedure are given in Table I.

Forging

Top plate forged to 5 in. by 5 in. by 9/16 in. and machined to 5 in. by 5 in. by ½ in.

Bottom plate forged to 10 in. by 6 in. by ½ in. and machined to 10 in. by 6 in. by 7/16 in.

Note.—The bottom plates did not forge to 12 in. and therefore ½ in. mild steel plate was welded on to provide the required length.

Heat Treatment

Normalised at 900 deg. C. for half-an-hour and air cooled.

Mechanical Tests

The majority of the test bars prepared for mechanical tests were cracked, and the results obtained are not considered worth recording.

Welding Tests

Modified Reeve fillet weld (Fig. 1).

Welding details in Table II.

Surface Contact

Good contact between the top and bottom test plates and between the bottom test plate and the jig plate was obtained by machining the former and grinding the jig plate.

Metallurgical Examination

(*a*) *Position of Sections.*—These were taken at 1½ in., 2½ in., and 3½ in. from the start of the weld and are numbered in Table III as 1, 2 and 3 respectively.

Table II.—Details of Welding Tests

Test	*Electrode	S.W.G.	Amps.	Time for 5 in. (secs.)	Length of Electrode used	Leg Length, Approximate
5517	Fastex 5	10	125	—	9 11/16 in.	1/4 in.
5517	,, 5	6	210	64	9 1/4 ,,	11/32 ,,
5518	,, 5	10	125	56	10 3/8 ,,	1/4 ,,
5518	,, 5	6	210	59	9 1/2 ,,	3/8 ,,
5519	,, 5	10	125	59	11 1/2 ,,	1/4 ,,
5519	,, 5	6	210	64	8 5/8 ,,	3/8 ,,

* Electrodes supplied by The Mond Nickel Co.
Baked at 110 deg. C. for two hours immediately before welding.

Test	5517 10 g.	5517 6 g.	5518 10 g.	5518 6 g.	5519 10 g.	5519 6 g.
Room temperature	18 deg. C.	19 deg. C.	20 deg. C.	20 deg. C.	21 deg. C.	21 deg. C.
Humidity	63 per cent.	58 per cent.	59 per cent.	47 per cent.	59 per cent.	60 per cent.
Time allowed between test runs	3 hours		2 3/4 hours*		2 3/4 hours	
Time allowed to stand before re'easing from jig	Overnight (18 1/2 hrs. approx.)		Overnight (18 1/4 hrs. approx.)		Overnight (18 1/2 hrs. approx.)	

Table III.—Details of Metallurgical Examination

Test and Section Number	Electrode	Equivalent Carbon per cent	Centre Section Weld Size by Leg Length (inches)		Centre Section Weld Size by Area (sq.in.)		Crack Incidence		Junction Zone Hardness $H_n/10$	
			V.	H.	$\frac{V \times H}{2}$	By planimeter	Vertical Leg Visual	Horizontal Leg Microscopical	Max.	Average
5517, 1	Fastex 5, 10 g.	0·62	—	—	—	—	Severe*	—	—	—
2	,, 5, 10 g.	0·62	0·23	0·25	0·029	0·024	Very severe	Fine cracks 0·007 in. long	421	399
3	,, 5, 10 g.	0·62	—	—	—	—	Complete parting	—	—	—
5517, 1	Fastex 5, 6 g.	0·62	—	—	—	—	Severe	—	—	—
2	,, 5, 6 g.	0·62	0·343	0·343	0·058	0·059	Very severe	None	421	384
3	,, 5, 6 g.	0·62	—	—	—	—	Complete parting	—	—	—
5518, 1	Fastex 5, 10 g.	0·65	—	—	—	—	Severe	—	—	—
2	,, 5, 10 g.	0·65	0·25	0·28	0·035	0·031	Very severe	Fine crack 0·004 in.	425	396
3	,, 5, 10 g.	0·65	—	—	—	—	Complete parting	—	—	—
5518, 1	Fastex 5, 6 g.	0·65	—	—	—	—	Severe	—	—	—
2	,, 5, 6 g.	0·65	0·343	0·375	0·064	0·065	Very severe	Fine crack 0·007 in.	402	389
3	,, 5, 6 g.	0·65	—	—	—	—	Complete parting	—	—	—
5519, 1	Fastex 5, 10 g.	0·65	—	—	—	—	Severe	—	—	—
2	,, 5, 10 g.	0·65	0·25	0·28	0·035	0·032	Complete parting	Marked crack 0·004 in.	423	403
3	,, 5, 10 g.	0·65	—	—	—	—	,, ,,	—	—	—
5519, 1	Fastex 5, 6 g.	0·65	—	—	—	—	Severe	—	—	—
2	,, 5, 6 g.	0·65	0·343	0·375	0·064	0·057	Complete parting	(Small cracks 0·0035 in. associated with inclusions)	429	395
3	,, 5, 6 g.	0·65	—	—	—	—	,, ,,	—	—	—

*Severe = Visual crack for 70 per cent. of vertical leg length.
Very severe = Visual crack for 100 per cent. of vertical leg length
Complete parting = 100 per cent. cracked in vertical leg for the full distance between the sections.

(*b*) *Period of Incubation.*—Release from the jig was made approximately 18½ hours after welding, and sectioning for micro-examination began approximately 20 hours after welding.

(*c*) *Crack Susceptibility.*—Determined visually and microscopically.

(*d*) *Hardness Surveys.*—Hardness tests were carried out on the centre sections (2½ in. from the start of the weld), the positions and values being shown in Figs. 2, 3, 4 and 5.

The results of the metallurgical examination, including weld sizes and maximum hardnesses, are given in Table II.

Comments

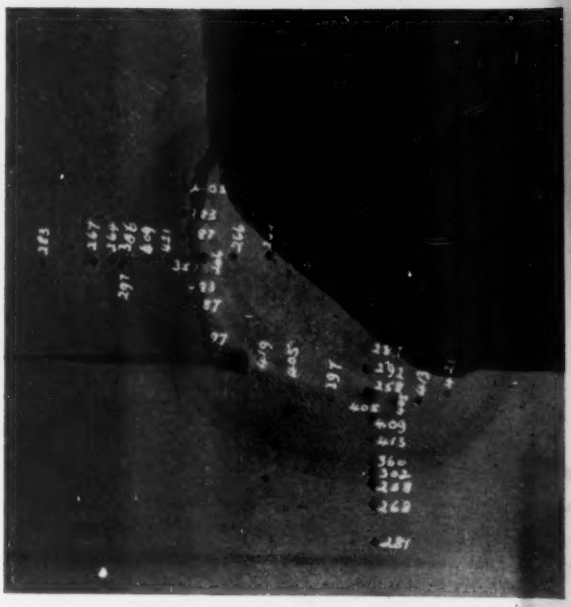
Several points of interest have been noted during the tests and examination.

(*a*) *Cracking during Forging.*—Fairly severe cracking was observed after forging. The test welds were free from such cracks, except that shown in Fig. 7, where a forging crack is seen in the vertical leg.

(*b*) *Cracking in Relation to Hardness.*—In general, the vertical leg junction zone has a slightly lower average hardness than the horizontal, but the tendency to cracking is much greater in the vertical leg.

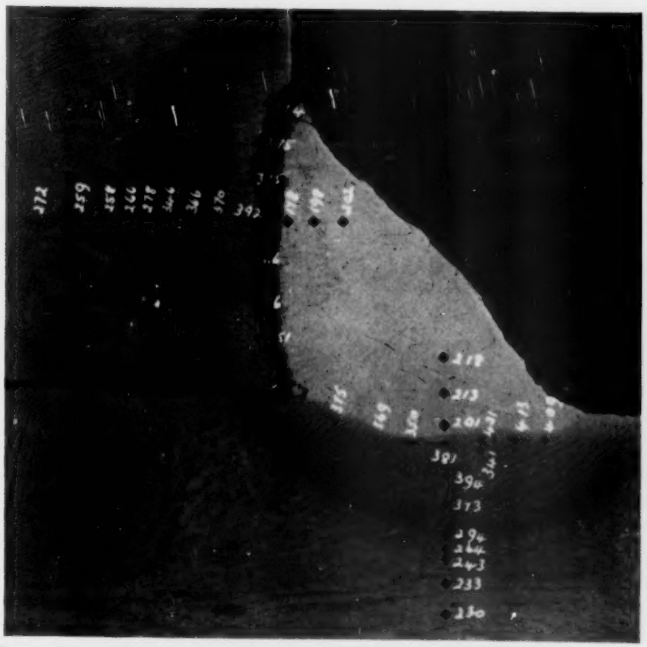
(*c*) *Position of Maximum Hardness.*—In the majority of sections there is a tendency for the hardness at the junction to be lower than at some positions nearer the inter-critical zone.

(*d*) *Severity of Cracking.*—The very severe cracking, leading to complete separation, would not appear to be in line with the relatively low alloy content, carbon content and hardening intensity.



x 6.5

Fig. 2. Cast SC 5617 10 s.w.g. Fastex 5 electrode.



x 6.5

Fig. 3. Cast SG 5617 6 s.w.g. Fastex 5 electrode.

Conclusions

The three casts of alloy steel No. 9, made for check weldability tests, have all shown severe cracking. The previous cast showed slight cracking, and the difference in degree of severity is probably due to the difference in time in the jig between the finish of welding and release for sectioning. Alloy steel No. 9 is evidently very susceptible to cracking when welded with Fastex 5 electrodes.

GENERAL CONCLUSIONS

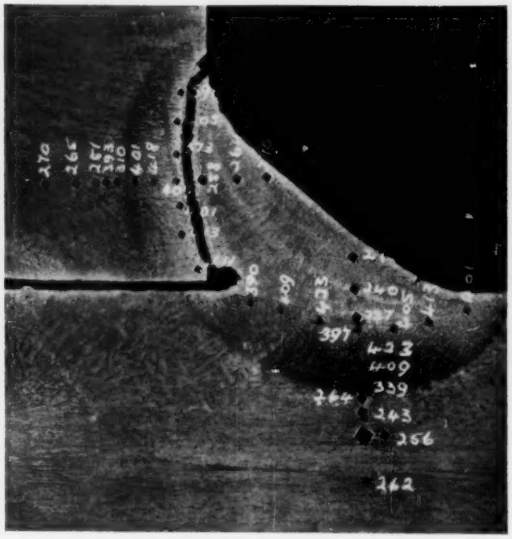
1. In an effort to develop a weldable low alloy high tensile steel having an 0·2 per cent. proof stress of 30 tons per sq.in., the following range of composition has been agreed. The steels should have a carbon content of 0·15 per cent., molybdenum 0·25 per cent., and contain varying amounts of manganese, chromium and nickel.

2. It has been shown that 18 lb. high frequency induction melts provide sufficient material for investigations into the weldability of a series of alloy steels.

3. The steel-making procedure was found to be reproducible between the three steel makers who were casting the billets after the conditions had been standardised.

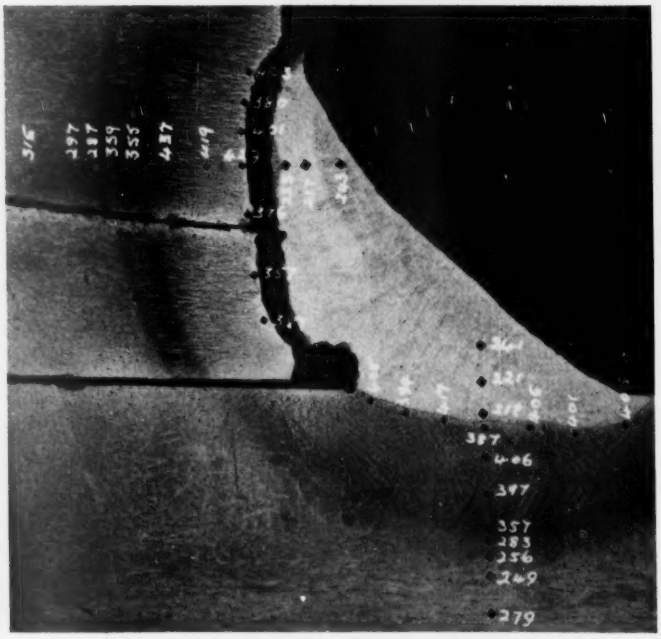
4. It was found that the modified Reeve test gives satisfactory and reproducible results in determining the weldability of these steels, providing the contacting surfaces between the top and bottom plate and the bottom plate and base plate (the heat sink) are prepared so as to provide good thermal contact.

5. In view of the reproducibility of these results which was finally obtained, it was desirable that investigations should be undertaken into the weldability and mechanical properties of the whole of the proposed series of steels in 18 lb. melts and the modified Reeve test.



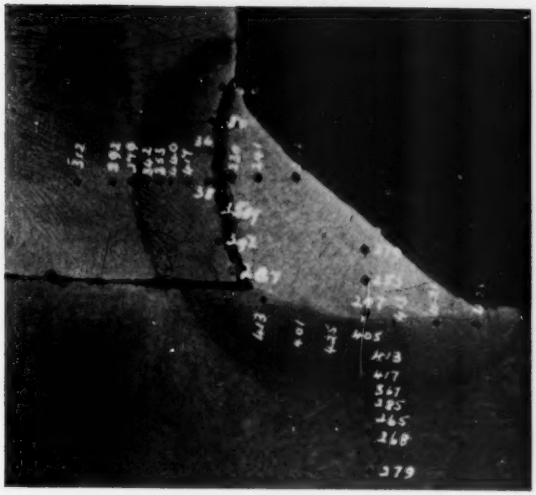
x 6.5

Fig. 4. Cast SG 5618, 10 s.w.g. Fastex 5 electrode.



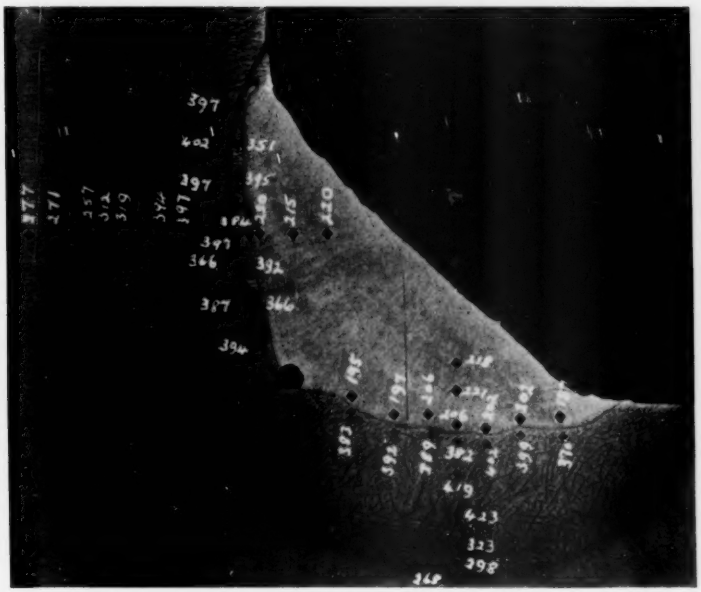
x 6.5

Fig. 5. Cast SG 5618, 6 s.w.g. Fastex 5 electrode.



x 6.5

Fig. 6.—Cast SG 5619, 10 s.w.g. Fastex 5 electrode.



x 6.5

Fig. 7. Cast SG 5619, 6 s.w.g. Fastex 5 electrode.

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